

# **REAL-TIME PRO-ACTIVE SAFETY IN CONSTRUCTION**

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# **REAL-TIME PRO-ACTIVE SAFETY IN CONSTRUCTION**

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Dedicated to my family and best friends; may I continue to make you all proud.

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## TABLE OF CONTENTS

ACKNOWLEDGEMENTS	iv
LIST OF TABLES	vii
LIST OF FIGURES	viii
SUMMARY	xi
CHAPTER 1: INTRODUCTION	1
1.1 Problem Statement and Research Objectives	1
1.2 OSHA Standards	4
1.3 Research Approach	5
1.4 Significance of Research	6
CHAPTER 2: BACKGROUND/LITERATURE REVIEW	7
2.1 Current Safety Practices	9
2.2 Existing Safety Technologies	10
2.3 Previous Studies and Current Applications	13
2.4 Blind Spots	15
2.4.1 Current Methods of Measuring	15
2.4.2 Current Methods of Correcting	19
CHAPTER 3: METHODOLOGY	24
3.1 Proximity Warning System	24
3.2 Automatic Blind Spot Calculation	25
3.2.1 Grid Representation of Machine	26
3.2.2 Ray Tracing	26
3.2.3 Blind Spots Statistics	29
3.2.4 Visibility of a Person from Driver's Perspective	30
CHAPTER 4: EXPERIMENTS & RESULTS	32
4.1 Technology Used	32
4.2 Results of Blind Spot Measurement	34
4.2.1 Manual Calculation of Blind Spots	35
4.2.2 Automatic Calculation of Blind Spots	39
4.2.2.1 Experiment 1	40
4.2.2.2 Experiment 2	45
4.3 Development of Proximity and Warning Device	51
4.3.1 Stage 1 – Preliminary Laboratory Testing	51
4.3.2 Stage 2 – Preliminary Harsh Field Condition Testing	53
4.3.3 Stage 3 – Final Field Trials	55
4.4 Evaluation	56

CHAPTER 5: FURTHER DEVELOPMENT	57
CHAPTER 6: CONCLUSION	59
REFERENCES	60
APPENDIX A: EXPERIMENT 1 FIGURES	63
APPENDIX B: 3D BLIND SPOTS VOLUME CALCULATION	88

## LIST OF TABLES

Table 4.1	Tabular Results for Blind Spot Percentages for Equipment	37
Table 4.2	Percent Blind Spots, Automatic Computer Tool	44
Table 4.3	Percent Blind Spots, Manual Calculation	45
Table 4.4	Percent visibility of person per location	50
Table 4.5	Device Consistency Measurements	55
Table B.1	Sphere Radius vs. # Cubes for Equal Cube Size	89

## LIST OF FIGURES

Figure 2.1	Accident Causation Swiss Cheese Model	8
Figure 2.2	Hazardous situation on work sites measured using 3D laser scan image	12
Figure 2.3	3D geometry of different poses of roller	12
Figure 2.4	Light bar method; view of ground level (left), view of 3 ft barrel (middle), view of worker bending down ( $< 5$ ft ) (right). (Fosbroke 2004)	17
Figure 2.5	Operator method diagram (Fosbroke 2004)	18
Figure 2.6	Virtual Reality method (Fosbroke 2004)	18
Figure 2.7	Ford blind spot systems (Ford 2009)	22
Figure 2.8	Surrogate camera placement (left) and enhancement camera placement (right). (National 2008)	23
Figure 3.1	Laser scan of a dump truck converted into grid model	27
Figure 3.2	Spherical co-ordinate system	28
Figure 3.3	Laser scanner FOV boundaries (HDS 2006)	28
Figure 3.4	Blind spots resulting from a small plate in the path of rays	29
Figure 3.5	Visibility of a person standing on ground at $x = -4$ , $y = -4$ , $z = -3.29$	31
Figure 4.1	Equipment Protection Unit (EPU) prototype	33
Figure 4.2	Personal Protection Unit (PPU) prototype	33
Figure 4.3	Laser Scan data of blind spots with visible regions from mirrors at 15m	35
Figure 4.4	Side Elevation of blind spots of Off-Highway Truck	38
Figure 4.5	Front Elevation of blind spots of Off-Highway Truck	39



Figure 4.6	Blind spots of bulldozer with 10 m radius: (left to right) ground level, 1.5 m tall person, operator eye level	40
Figure 4.7	Bulldozer manual blind spot calculation in AutoCAD using laser scan “modelspace”, hatched region represents blind spots	41
Figure 4.8	Blind spots of truck with 10 m radius: (left to right) ground level, 1.5 m tall person, operator eye level (see Appendix A for full figures)	41
Figure 4.9	Pick-up Truck manual blind spot calculation in AutoCAD using laser scan “modelspace”, hatched region represents blind spots	42
Figure 4.10	Clean (left) and dirty (right) windshield comparison	43
Figure 4.11	Bulldozer floor view of laser scan computer interface	47
Figure 4.12	Bulldozer roof view of laser scan computer interface	48
Figure 4.13	Computer method coordinate layout for bulldozer	50
Figure 4.14	Percent visibility of person at location C	51
Figure 4.15	Spider-map of Safety Zone for PPU around EPU	53
Figure 4.16	Active proximity warning zone	54
Figure 5.1	Flowchart of Information Flow – Value-added Interactions	58
Figure A.1	Bulldozer blind spots eye level ( $z = 0$ m); $r = 10$ m.	64
Figure A.2	Bulldozer blind spots 1.8 m tall person ( $z = -0.74$ m); $r = 10$ m.	65
Figure A.3	Bulldozer blind spots 1.5 m tall person ( $z = -1.04$ m); $r = 10$ m.	66
Figure A. 4	Bulldozer blind spots ground level ( $z = -2.54$ m); $r = 10$ m.	67
Figure A.5	Pick-up Truck blind spots eye level ( $z = 0$ m); $r = 10$ m.	68
Figure A.6	Pick-up Truck blind spots 1.8 m tall person ( $z = 0.34$ m); $r = 10$ m.	69
Figure A.7	Pick-up Truck blind spots 1.5 m tall person ( $z = 0.04$ m); $r = 10$ m.	70
Figure A.8:	Pick-up Truck blind spots ground level ( $z = -1.46$ m); $r = 10$ m.	71
Figure A.9	Dump Truck blind spots eye level ( $z = 0$ m); $r = 10$ m.	72

Figure A.10	Dump Truck blind spots 1.8 m tall person ( $z = -1.49$ m); $r = 10$ m.	73
Figure A.11	Dump Truck blind spots 1.5 m tall person ( $z = -1.79$ m); $r = 10$ m.	74
Figure A.12	Dump Truck blind spots ground level ( $z = -3.29$ m); $r = 10$ m.	75
Figure A.13	Roller blind spots eye level ( $z = 0$ m); $r = 10$ m.	76
Figure A.14	Roller blind spots 1.8 m tall person ( $z = -0.79$ m); $r = 10$ m.	77
Figure A.15	Roller blind spots 1.5 m tall person ( $z = -1.09$ m); $r = 10$ m.	78
Figure A.16	Roller blind spots ground level ( $z = -2.59$ m); $r = 10$ m.	79
Figure A.17	Excavator blind spots eye level ( $z = 0$ m); $r = 10$ m.	80
Figure A.18	Excavator blind spots 1.8 m tall person ( $z = -0.77$ m); $r = 10$ m.	81
Figure A.19	Excavator blind spots 1.5 m tall person ( $z = -1.07$ m); $r = 10$ m.	82
Figure A.20	Excavator blind spots ground level ( $z = -2.57$ m); $r = 10$ m.	83
Figure A.21	Motor Grader blind spots eye level ( $z = 0$ m); $r = 10$ m.	84
Figure A.22	Motor Grader blind spots 1.8 m tall person ( $z = -0.88$ m); $r = 10$ m.	85
Figure A.23	Motor Grader blind spots 1.5 m tall person ( $z = -1.18$ m); $r = 10$ m.	86
Figure A.24	Motor Grader blind spots ground level ( $z = -2.68$ m); $r = 10$ m.	87
Figure B.1	Dump Truck 3D Blind Spots – Equal Cube Size	90
Figure B.2	Bulldozer 3D Blind Spots – Equal Cube Size	90

## SUMMARY

Collisions between personnel on foot and heavy equipment or materials on a construction site can be characterized as a contact collision. These types of incidents are a common occurrence on a work site. Technology is needed to improve work zone safety by alerting workers that are in danger of collisions pro-actively and in real-time. Developing this technology may assist in collecting previously un-recorded data on “near-misses” (close-calls). An approach is presented in this paper that is based on wireless radio frequency technology to alert workers in real-time when they are in danger. Various experiments are described that have been conducted in order to gain better understanding of the technology’s potential, including measuring equipment blind spots and alert (or safety) zones.

Blind spots areas are measured for six common construction vehicles to help determine the required (or minimum) alert distance (safety zone) for the equipment. A computer program was developed in-house to automatically calculate the percentage of blind spots on 2-dimensional planes and in the overall 3-dimensional volume. The blind spots results directly indicate the necessary safety zones for the equipment.

The proximity device results show that technology demonstrated the capability of collecting important safety data while pro-actively detecting hazardous situations and warning workers and equipment operators during imminent potential hazardous events. Furthermore, the presented research can lead to improve the overall safety performance in construction and elsewhere through improved learning and education by providing relevant information to decision makers at all levels.

## **CHAPTER 1: INTRODUCTION**

### **1.1 Problem Statement and Research Objectives**

A construction work zone is mostly a dynamic space consisting of resources such as personnel, heavy equipment, materials, and built structures that can be in relative motion to each other. The sometimes unstructured or almost random movement of resources can lead to incidents between at least two objects. These incidents can then be characterized, for example, as contact collisions and are often a threat to the safety of personnel that is in too close proximity to equipment. These collisions can be attributed to various problems that begin with the closeness in which vehicles and workers operate. Pratt, et al. (2001), described how workers are often unloading materials from a vehicle for an extended period of time or are repairing other vehicles, and operators become unaware that workers remain in proximity. The cause for such actions is workers become unaware of their surroundings due to fatigue and task repetition, which causes lower awareness and loss of focus on surroundings (Pratt et al., 2001). These situations become dangerous for all workers that are in proximity, and in particular when workers move into spaces that are not visible to equipment operators. To avoid workers to be in such blind spots, an alert system is needed that will alarm workers and equipment operators at the same time, and inform them of their surroundings.

Blind spots on heavy construction equipment are a leading cause of contact collisions in the construction industry; creating problems for operators by restricting their line of sight and eliminating their view of personnel and small equipment. The Bureau of Labor Statistics published Census of Fatal Occupational Injuries (CFOI) safety statistics

for year 2007. The 2007 CFI revised report was released in April 2009. The construction industry alone accounts for 21.3% of all occupational fatalities – 1,204 of 5,657 (total fatalities reported for 2007). The construction industry rate of fatal occupational injuries equals 10.5 per 100,000 workers. The annual total (all fatal occupational injuries) rate was 3.8 per 100,000 workers; “the 2007 fatality rate remains the lowest fatal work injury rate ever recorded by the fatality census” (CFI 2009). Accident causation investigations and other historic safety statistics within the past decade show high numbers of fatality rates for personnel being struck by vehicles. Within the construction industry, most fatalities of workers being struck by objects occurred in heavy construction and to specialty contractors, 10% and 13% of all construction-related fatalities, respectively. Other statistics indicate that 6% of all occupational injuries were from workers being struck by vehicles (CFI 2007). This information indicates that there is a need for a warning device that alerts workers when they are in danger and gives them a “second chance”.

These 2007 CFI statistics coincide with the statistics from previous years; it is evident that not much has improved in preventing workers from being killed by vehicle contacts. In addition, statistics between the years 1992 and 1998 show that out of the 465 vehicle related construction fatalities, 318 of the fatalities were workers on foot. The type of vehicle they were struck by was most commonly a type of truck (60%) followed by a construction machine (30%). 110 of the 465 fatalities occurred to equipment operators; of these fatalities more than half of the accidents occurred to an equipment operator who was operating a construction vehicle (53%) followed by operators who were driving a truck. The remainder of the 465-recorded fatalities occurred to

supervisors and other personnel. The majority of the fatalities (51%) occurred when a vehicle was in reverse mode; this can be attributed to the large amount of blind spots that are prevalent in the backside of a vehicle (Pratt et al., 2001). Other statistics that focus on road construction show that during the year 2006, 589 workers were reported killed by being struck by an object. This number overall accounted for 10% of all occupational deaths. Of these, 369 workers were killed by a motor vehicle during highway construction that accounted for 7% of all occupational deaths (CFOI 2007).

Fosbroke (2004) identified within the construction research program, created by the National Institute for Occupational Safety and Health (NOISH), the following contributing factors to solve for the issue of contact collisions: (1) A lack of knowledge of specific risk factors exists; (2) All causation data collected on incidents is collected after-the-fact, and (3) No real-time information is gathered during the incident. Existing practices report that the causation and specific safety needs on a site have yet to be recorded and sufficiently identified. In addition, in the construction industry there is insufficient adaptation of intervention of technologies used in other industries. For practical implementation and evaluation, the railroad and mining industry both are testing various prototype technologies which once adapted, could be used in the construction industry. However, there is a lack of scientific evaluation for newly and existing intervention technology. Emerging safety technology needs to be thoroughly evaluated in research using current or newly developed evaluation methods along with case studies and data analysis. These described issues will be addressed in this research through the evaluation of current safety practices, uses of technology in safety, creation of pro-active

safety technology using embedded radio frequency (RF) technology, and subsequent evaluation of the technology.

## **1.2 OSHA Standards**

The Occupational Safety and Health Administration (OSHA) sets forth minimum guidelines to protect the health and safety of those working in the construction industry and other occupational fields; construction safety can be found in 29 CFR 1926 OSHA Construction Industry Regulations. Equipment operators have limited line of site; regulations to protect workers and equipment operators from collisions are outlined in Subpart O. In this subpart, regulation §1926.601(b)(4-4ii) discusses the necessity to have a clear rearview, however this can be bypassed with the use of a reverse horn or the use of a signaler. §1926.601(b)(5) discusses the need for a crack-free window with a clear view; later regulations discuss this same need for all types of heavy equipment. OSHA standards can be modified with a special request, §1926.602(a)(8)(i) explains the ability to change the brake and fender system of heavy earth moving equipment if a special requests is given and approved, the safety of the equipment working in the work zone cannot be compromised. Changes to the heavy equipment when it comes out of the manufactures warehouse for real world used on the construction site are permitted through written consent from the manufacturer to the equipment owner per §1926.602(c)(1)(ii), this regulation states that the safety of the equipment cannot be compromised.

Research shows that equipment on the construction site may be modified to meet the specific needs of the equipment owner and of the work on the site; each project is

different and modifications may be necessary to get the job done safely. Currently, blind spot measurements have been conducted on original equipment made by the manufacturer. Therefore, the blind spot measurements presented in this paper have been measured on unmodified heavy equipment in the construction environment. Furthermore, it was observed that some equipment is not compliant with OSHA regulations (e.g., cracked windshield) and therefore is not helping to prevent accidents. The true blind spots of the equipment as seen by the operators on a daily basis need to be measured as an accurate representation of the potential adverse conditions present in the workplace, such as low visibility due to dust or cracked glass.

### **1.3 Research Approach**

In order to help remediate dangerous situations, workers will be alerted with the RF proximity devices – the personal protection unit (PPU) for ground workers and the equipment protection unit (EPU) for heavy equipment operators – giving the workers a “second-chance” to avoid an incident. Experiments to determine the read range of the RF proximity equipment will be conducted in ideal and construction conditions.

The current methods of aiding blind spots are inconclusive because they do not show the actual blind spots of the vehicles but the estimated blind spots. Blind spots will be calculated manually using laser scan data in a CAD program. Blind spots will also be automatically calculated using a computer tool – this method is more precise. Both the manual and computer results will be compared and conclusions made on the effectiveness of both methods. This research aims to collect real and accurate data on the blind spots present on construction vehicles. Since OSHA allows for adjustments to be made to



construction vehicles such that they can be used for the needs of the equipment owner, it is important to check the blind spots of vehicles as they are on the work site. This research collected blind spots using a Laser Scanner from heavy equipment on an actual working construction site. Previous research offers recommendations on placement of proximity systems, whereas this research strives to identify and quantify the necessary (or minimum) safety zone required for equipment analyzed. A 3D library of blind spots and recommended safety zones will be developed through conducting these experiments.

#### **1.4 Significance of Research**

The proximity devices will provide the alarms and disrupt the worker's focus on his/her work task, forcing the worker to reassess the surroundings; too often do accidents occur because workers are "used-to" or "comfortable with" the surrounding work environment, including equipment operators, based on "common sense" and "practical experience". The "second-chance" offered to the workers is a new, pro-active method to avoid accidents, and is not currently widely used throughout the construction industry. This research will also help develop a better means of "implementing" this technology into the work site activities and worker acceptance and trust of the technology. This research will provide a foundation for further research to develop a system to record "near-misses" and general "real-time data" of an incident, which is currently not practiced largely throughout the construction industry. This research will provide scientific evaluation of the proximity technologies and further analyze equipment blind spots, and strive to identify necessary safety zones for heavy construction equipment.

## **CHAPTER 2: BACKGROUND/LITERATURE REVIEW**

Reported in many research reports, OSHA (Occupational Safety and Health Administration) regulations help, but are not enough to prevent collisions from occurring. In research conducted through the Center for Disease Control (CDC), Pratt, et al. (2001) studied to categorize the various kinds of fatalities that occur on a construction site, both along and off highways. All gathered information was based on after-the-fact (after the incident occurred) data.

The statistics presented earlier (CFOI 2007) coincide with the statistics from previous years; it is shown that not much has improved in preventing workers from being killed through contact collisions with vehicles and/or equipment. In addition, statistics between the years 1992 and 1998 show that out of the 465 vehicle related construction fatalities, 318 of the fatalities were workers on foot. The type of vehicle they were struck by was most commonly a type of truck (60%) followed by construction equipment (30%). The study reported that 110 of the 465 fatalities occurred to equipment operators; of these fatalities more than half of the accidents occurred to an equipment operator who was operating a construction vehicle (53%) followed by operators who were driving a truck. The remainder of the 465 recorded fatalities occurred to supervisors and other personnel. The majority of the fatalities (51%) occurred when a vehicle was in reverse mode; this can be attributed to the large amount of blind spots that are prevalent in the backside of a vehicle (Pratt et al., 2001).

Other statistics that focus on road construction show that during the year 2006, 589 workers were reported killed by being struck by an object. This number overall

accounted for 10% of all occupational deaths. Of these, 369 workers were killed by a motor vehicle during highway construction, accounting for 7% of all occupational deaths (CFOI 2007).

Technology may be used as the “first and last barrier” in incident prevention. The causation model for accidents (Figure 1) has been adapted from Reason’s (1990) Swiss Cheese Model. The model shows how in each level of construction the “holes” in an organization’s safety plan lead to unsafe actions and thus a higher probability of incidents (injuries and fatalities).

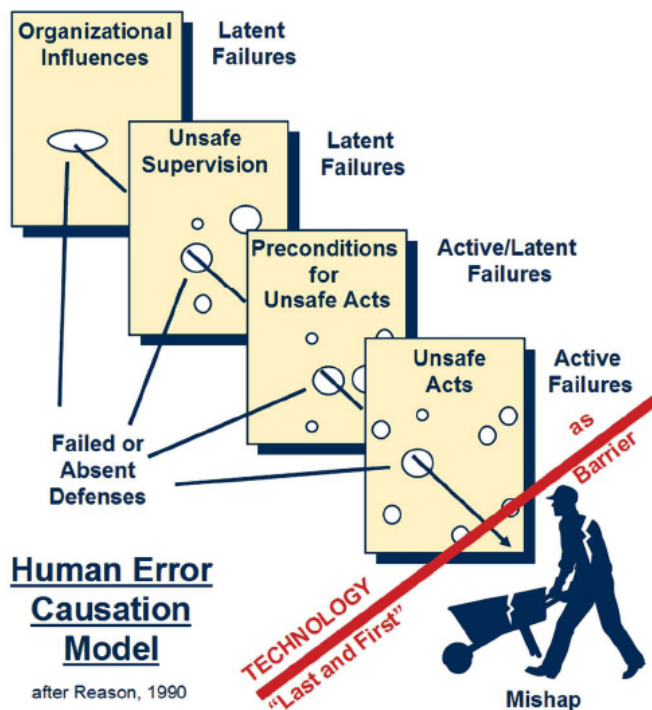


Figure 2.1: Accident Causation Swiss Cheese Model (Reason 1990)

Smart technologies need to emerge in the construction industry to help improve organizational and site safety conditions. Technology can be used twice: once as a final barrier by giving workers a “second chance” of escape using real-time-proximity-warning devices (bottom-up), and secondly, using the data these devices can record to derive information from previously unrecorded events such as “near-misses”. This new

information can lead to changes in existing organizational safety practices (top-down). Effective implementation will strive to close-up the “holes” and decrease the number of accidents on worksites. As a result of changes in the organization of safety within companies, technology will become a first barrier tool of safety.

## **2.1 Current Safety Practices**

There are different methods of maintaining safety in work zones including the modification of behavior methods employed “passive safety” technology, and “active safety” technology. Current safety practices include OSHA mandated practices such as the use of hard hats and safety glasses as well as the behavior of individuals on the work-site. Pratt et al. (2001) discovered that the first method to improve safety on a work zone is by altering the behavior of the individuals inside the work zone. Purdue University, in conjunction with CII, discovered that behavior based safety can be an effective tool in increasing the safety of a work-zone. The methodology includes allowing workers to monitor one another and then discuss the issues they discovered to try and improve each others safety habits. However, it was discovered that this method can be limiting because of the changes that occur daily on the work-site, such that the suggested improvements could become aloof. Also, with the increased behavioral awareness supervisors may become unaware of the tangible hazards that are present (Purdue, 2004). Furthermore, it is necessary to maintain a certain level of health and fitness during the work day. If a worker becomes ill he or she should rest until all physiological functions have returned to normal (Uwakweh, 2002).

The Construction Industry Institute (CII) (2003) reported “the better safety records occurred when site-specific safety programs were prepared for the projects” (University of Texas 2003). Therefore it can be assumed that better front-end-planning of, or design for safety will result in safer worksites.

## **2.2 Existing Safety Technologies**

Safety practices must be implemented as safety technologies are implemented. Passive safety technology does not use any sensing technology and once installed, for example, helmets, goggles, or safety vests, does not provide any further feedback. Active safety technology uses sensing and data recording technology and works in two different ways; the first is with two or more wireless sensors that transmit information to each other and the second is the use of optical cameras that detect and potentially identify objects through image processing. Within active safety technology there is a distinct difference between re-active and pro-active safety technology. Re-active technology collects data in real time that can then be analyzed to determine the best way to change future situations to make improvements. Pro-active technology works in real-time to alert personnel of the dangers occurring at that moment.

The aforementioned safety techniques have been unable to eliminate contact collisions on work sites that occur daily. One method of improving safety is using technology that is integrated into the barriers that are already present on a construction site. This technology is pro-active safety technology because it alerts workers of an immediate threat. There are various systems available that employ an alarm into the barrier cones, these are most useful for road side construction. If a cone is hit by a driver

that is not paying attention then an alarm is triggered and the workers can be alerted of the breach into the construction site. These cones can be set up to create barriers inside of construction sites in an area where heavy equipment is not being utilized by creating a safety zone. If an operator accidentally enters into the safety zone than the workers within the zone are alerted (Kocher 2006).

Re-active safety technology may also include the use of video cameras, where the cameras would allow supervisors and owners to assess the safety status of a project on a daily basis. Assessments may include features like the impact of the weather, accurate accident investigations, and asset tracking. This information can then be used as a way to improve the productivity of the work site, monitor the safety by noting any potential hazards, and note any breach of regulation by workers and sub-contractors (Abeid and Arditi 2002). Cameras can also be used as a pro-active method by transmitting the feedback to a hub and incorporating the data with detection and tracking algorithm can choose a worker, material, or piece of equipment to track in 3D real-time. This method gives a virtual picture of the object selected and allows the tracker to monitor any potential threatening situations that could endanger the work zone.

Laser scanning is also used in a re-active manner to improve the safety of a worksite. A laser scanner can collect three-dimensional (3D) point clouds of objects in its field-of-view. Accurate 3D models of the entire worksite can be assessed in the same ways video cameras work. By taking digital images of project sites in real-time, all project coordinators are able to monitor the progress through a virtual environment. Owners can then locate tasks or areas that are unsafe and inform workers of the issue without entering the site. Laser scanning will be used in this research as a way of

discovering the blind spots on different pieces of equipment. Figure 2.2 is a digital image taken by a laser scanner that shows the dangerous situation a worker can be found in daily work tasks. This image can be monitored and noted such that the supervisors warn workers of the hazards. Figure 2.3 also shows how laser scanning can be used when taking digital images of equipment to be used when determining the blind spots of equipment; these images are from a 360 degree scan of a roller.

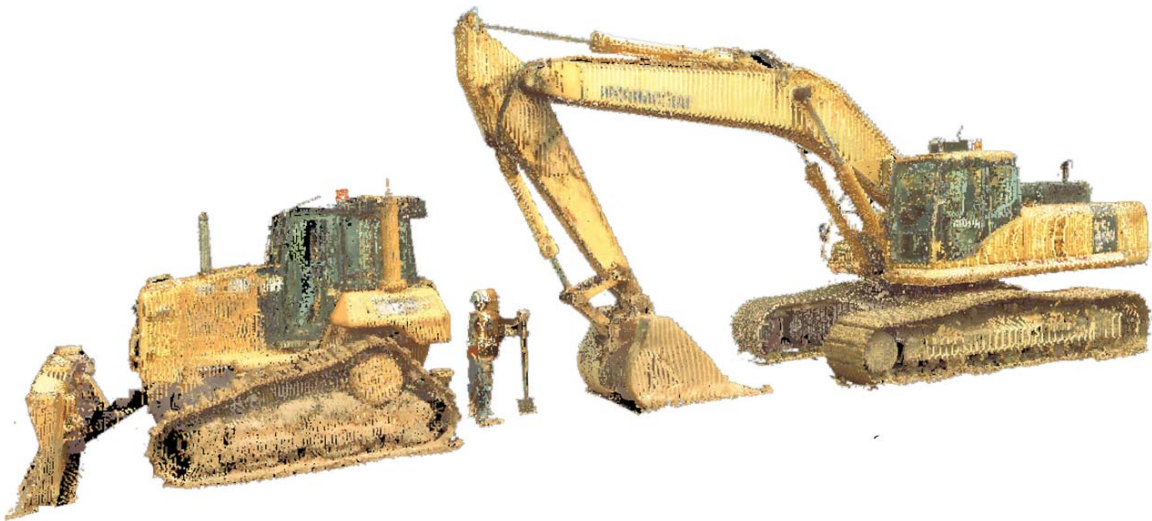


Figure 2.2: Hazardous situation on work sites measured using 3D laser scan image



Figure 2.3: 3D geometry of different poses of roller

Radio Frequency Identification (RFID) can be used as a pro-active safety measure. Active RFID contains an internal power source and mostly has been used as a method of tracking the location of various resources in the combination with Global Positioning Systems (GPS) (Song et al. 2006). Although this method has allowed supervisors and owners to monitor the movement and analyze ways to improve the site by increasing efficiency in a reactive manner, cost of implementation is high and due to the size of some of the sensing equipment, not very practical. However, RFID transfers data in real time, and is capable of observing real-time movements. An antenna, which reads the RFID from various distances depending on the tag being used, can be mounted within a truck along with a small alarm. When the antenna reads the tag the alarm will be triggered, which will alert the equipment operator that a worker on foot is nearby. This research focuses on the use of radio frequency technology alerting workers; active RFID technology can also pro-actively alarm workers when equipment, ground personnel, and materials are in close proximity of each other.

### **2.3 Previous Studies and Current Applications**

Similar studies have been done to implement safety technologies onto construction sites to improve the safety of workers. NIOSH created a prototype called HASARD that uses a magnetic sensing system. Magnetic waves are emitted from a transmitter and whenever the magnetic wave is interfered with an alarm is triggered. The system is oriented in such a way that the transmitter is a magnetic loop that is coiled to condense the system and decrease the amount of power emitted yet still making it effective (Schiffbauer 2001). The prototype was tested for six months in a mine; a mine was chosen for the test



because of the extremely harsh conditions (Schiffbauer and Mowrey, 2001). The sensors were placed on people and walls to prevent collisions from a Continuous Miner (CM), a machine used to mine underground. The signal was found to penetrate through all coverings and could be calibrated to be used above ground as well.

Aker Yards, a shipping yard in Turku, Finland, has implemented active RFID tags to monitor workers as they embark and disembark along the entry bridges to the various ships. This allows for fire and rescue to monitor in real-time the head count of all personnel on the boats in case of an emergency. Also, it allows for fire and rescue to quickly realize if someone has been on the boat for an exorbitant amount of time, in which they could be injured or trapped in some area of the ship. The tags also held important information about the worker including a picture to verify the person found was the right person in the helmet (Vilant 2008).

New systems using RFID technology are emerging to protect firefighters from becoming lost; being trapped or lost is the third leading cause of deaths in the field. Some tracking systems use a high frequency to prevent signal bounce and increase line of sight to the victim (Scott 2006). Other systems use lower frequency but use various transmitters to pass the signal along; this allows fire fighters to orient themselves as to where they are located within the area (Exit, 2008).

A third system that is used to protect firefighters does not use RFID technology but uses ultrasound technology to transmit signals. The firefighter wears a pack that contains a transmitter on both the front and the back. When the firefighter falls down and becomes motionless the transmitters go into alarm mode and send signals out to the receiver that senses the direction and location of the firefighter (SURVIVAIR 2005).

RFID has also been seen in warehouses, mines, and train depots being used as a safety mechanism. In warehouses, forklifts pose a large threat to the safety of all workers due to blind spots and the small spaces in which they work; additional blind spots are created in such tight areas of operation. To warn workers on foot, warehouses have put RFID technology at corners that trigger alarms when a forklift is in proximity of the sensors. Furthermore, the forklifts can be tracked throughout the warehouse and monitored for any potential dangerous situations. The rail industry has implemented RFID technology to warn train mechanics working on the tracks of an oncoming train. They use active RFID that projects the signal at a very high frequency (over 30 Hz) since trains move at an extremely high velocity and workers need sufficient time to clear the tracks and any equipment they are using. The technology used in the train industry is very similar to that which is used in our project.

## **2.4 Blind Spots**

### **2.4.1 Current Methods of Measuring**

There is limited research in the field of measuring blind spots, thus far, most methods to correct blind spots is done by intuition and making assumptions as to where there are blind spots present. A study has been done at IRSST (Occupational Health and Safety Research Institute) in Quebec called *Measurement and evaluation of blind spots in trucks* to determine the blind spots of three different pieces of heavy equipment all relating to hauling trucks. The blind spots on the vehicles were determined through the observation of vehicle movements and 28 interviews of drivers who discussed their visibility issues. It was found that a truck cab alone inhibited 59 to 76% of visibility; a

24-foot trailer attached to the cab reduced the visibility by 80%. They noted that the diameter and curve radius of the mirrors varied from truck to truck, and the mirrors would have to be angled uniquely on each vehicle to improve visibility (Larue and Giguère 1992).

NIOSH did a report on potential systems that could aid the issue of low visibility in heavy equipment. Their first step was to determine the blind spots of the equipment that caused operators to (1) run over people and materials, (2) come into contact with other equipment and materials, and (3) rollovers. Four different methods to determine blind spots were devised, two manual and two computer aided. All methods were conducted on the same dozer and in an area free of obstructions. The dozer was placed in the center of a circular grid that had lines drawn out on the ground at every 10 degrees. The first manual method was done by placing a light bar in cab of the equipment and making note on the grid that was drawn out on the ground; this information was then transferred to a paper to create a spider-diagram displaying the area of obstruction; the area where the light was not seen was noted as a blind spot. Figure 2.4 shows the results of the light bar method measuring the ground level, a three foot tall barrel, and while a worker was bending over (< 5 ft). The area of visibility is the white region and the blind spots are the dark region.

The second method was done with an experimenter sitting in the cab. The same grid was used as in the light operation method. This time experimenters acted as workers and walked around the equipment and made notes when the operator could not see them. Figure 2.5 shows the results of the operator method; dark areas imply blind spots.

The third and fourth methods used virtual reality and high-quality photographs, respectively, both using computers. A full laser scan of the outside of the equipment was acquired and then the experimenters super-imposed themselves virtually into a 3D CAD model of the cab of the equipment created with the laser scan. Figure 2.6 is a view from the cab as well as the virtual grid used and the results gathered. The photograph method used a mounted camera in position relative to the operators head position, as to obtain the driver's perspective. The photos were stitched together and analyzed on the computer. No diagram was available for this method. (Fosbroke 2004)

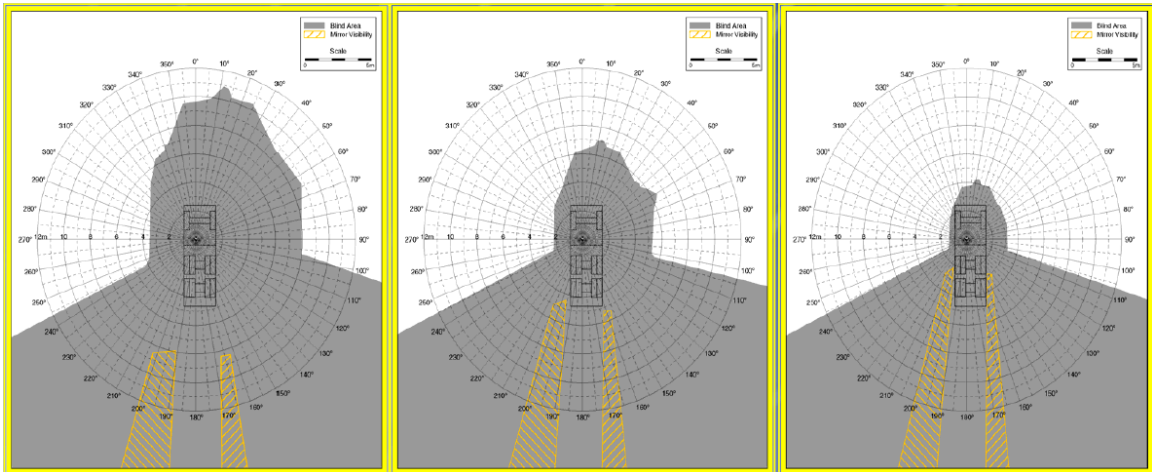


Figure 2.4: Light bar method; view of ground level (left), view of 3 ft barrel (middle), view of worker bending down (< 5 ft ) (right). (Fosbroke 2004)

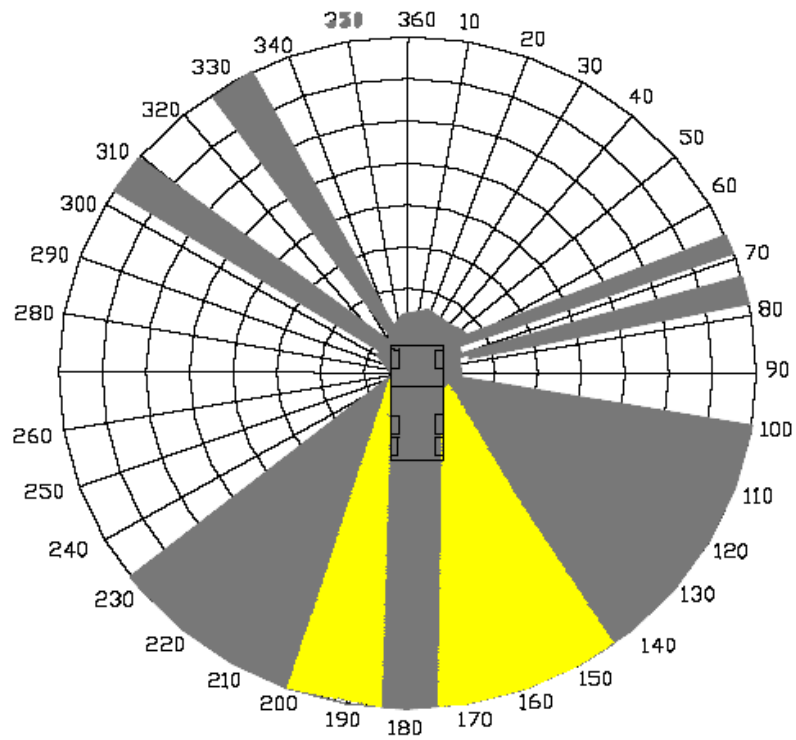


Figure 2.5: Operator method diagram (Fosbroke 2004)

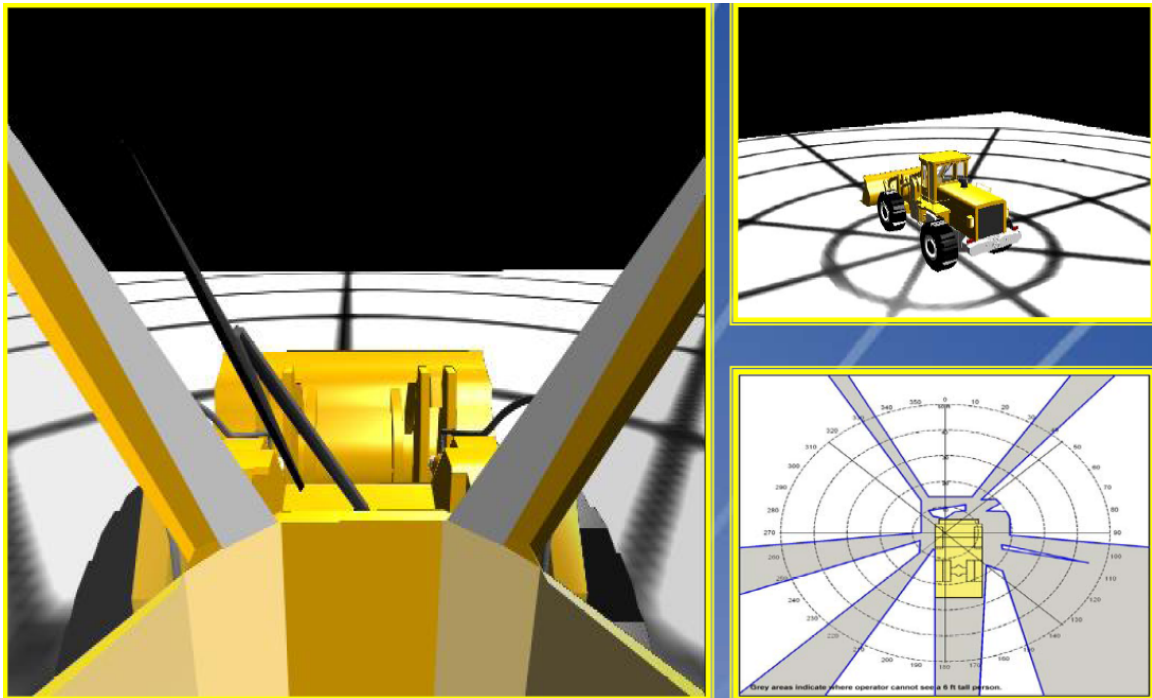


Figure 2.6: Virtual Reality method (Fosbroke 2004)

#### 2.4.2 Current Methods of Correcting

The first step in improving the problem with blind spots is through behavior modification. Proper training is the first step to ensure safety; operators and ground personnel must be trained in how to work around heavy equipment. Personnel must establish a safe driving checklist involving site clean-up and vehicle maintenance as well as ensure that the equipment being used for the job is the proper piece of equipment for the task at hand (Health 2002). The site layout must be made to allow for equipment to pass by pedestrians without obstruction, an ITCP (Internal Traffic Control Plan) should be created to ensure the proper use of roadways, hand signals, and signs to be use within the construction site (Pratt). Turning movements can be limited by creating turn-around areas that limit the need to reverse; also, lighting must be sufficient on the construction site to ensure the most visibility possible (Health 2002).

Representing NIOSH, Ruff and Hession-Kunz studied RFID technology focused on preventing contact collisions. Ruff, et al. determined that existing off-the-shelf RFID systems did not meet their in-house standards for the harsh mining environment. NIOSH chose to contract with IDI to develop a “low-cost, highly reliable [RFID] system”. Worker tags were attached to hard hats, and the equipment tags were installed on the front of the tested equipment during the experiment. “Detection was not dependent on the physical orientation of the pedestrian” (Ruff et al. 1998).

Ruff conducted a study on dump trucks located on surface mines; this environment was selected due to its harsh environment and large amount of blind spots on the haulage trucks. The experimenters studied three possible aids in correcting blind spots: electromagnetic signal detection, radar, and video cameras. The electromagnetic

works by alerting workers and drivers together; the equipment has an antenna that reads the tags located on the workers. Radar works by warning the equipment operator that a worker or obstacle is in the radar beam; this method is prone to false alarm and has a limited range. Research shows that radar would be most effective for smaller equipment. Video cameras were also studied and proved to be most beneficial when collaborated with other methods, the operator can check the cameras once an obstacle is detected to check for false alarms. (Ruff 2001)

In 2007, Ruff published “Recommendations for Evaluating and Implementing Proximity Warning Systems on Surface Mining Equipment”, in which he reported on fatal accidents caused because the victims were in a blind spot area on heavy equipment, and focused on methods of eliminating blind spots. Ruff analyzed five large surface mining equipments during his experiment. The blind areas were measured for the ground level plane and for a 1.5 meter tall person or object. Mirror visibility was also measured and plotted against the direct blind spots. Of the equipment analyzed, all had significant blind spots to the rear of the equipment. (Ruff 2007)

Hefner contracted with the CDC to ‘obtain diagrams of the blind areas around 24 different vehicles or machines that are used in the construction industry’ (Hefner 2003). The study included dozers, loaders, backhoe loaders, graders/scrapers, and haul trucks. The procedure was well documented, but no recommendations were concluded – add the data to a knowledge database.

Most blind spots aides are used when a vehicle is in reverse. One application uses a two-zone method, the first zone which is the near zone is a wide and short emission of infrared. The second zone is a thin long zone used to detect objects that are far away.

This allows for the system to track objects and note if they are coming closer, there are various sensors on the vehicle that collect information including object classification (class = near or far), tracking (tracks objects in class), estimation (characterizes threat), kinematics (tracks locations through wireless control area network) (FreshPatents 2008).

The next system uses algorithms that detect, track, and warn drivers when an object is in it's blind spot. The two sensors are located on each side mirror and emit a signal similar to UMRR (Universal Medium Range Radar). This system works both at low and high speeds and detect from 0.3 meters to 8 meters. The sensors can work together or be incorporated into a third medium. The warning sign is included in the sensor and illuminates when the sensors track something (Smartmicro 2008).

One automobile maker has created two different blind spot remedies. The first remedy includes the use of small blind spots mirrors that are added to the original mirrors. They fit within the required mirrors but are convex, which allow the driver to see more (these alone are illegal in the U.S.). The second remedy is with the use of a blind spot monitoring system and cross traffic alert system. Figure 2.7 is an image of the two methods working together. The systems used beam radar modules located on the side and rear of the vehicles. The cross traffic can notice vehicles coming from the side at all angles and not just 90 degrees (Ford 2009).



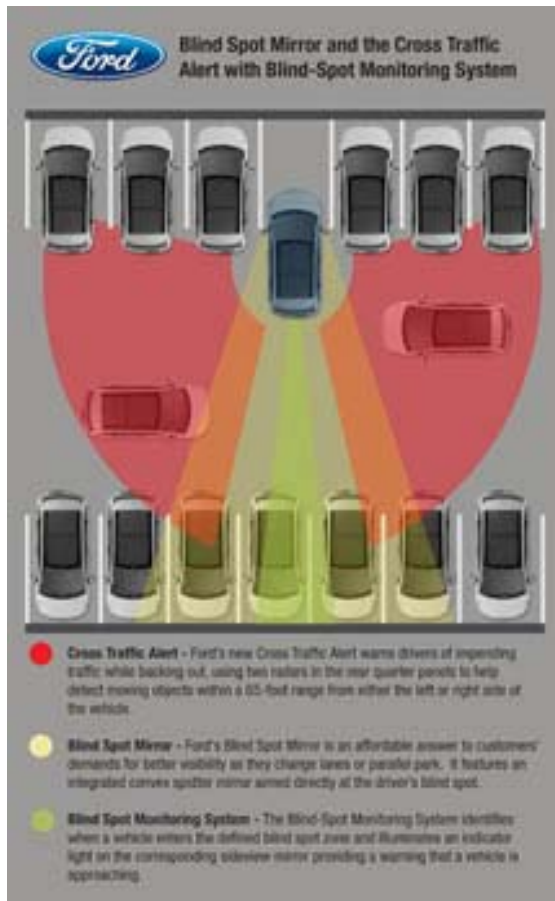


Figure 2.7: Ford blind spot systems (Ford 2009)

Thus far, cameras have seen the biggest use in aiding the low visibility of large machinery. One project uses cameras as surrogates to mirrors and enhancements to visibility. Surrogate cameras replaced the common visibility of mirrors, however since these are such vital images there has to be an available clamp-on mirror that can be used in case the system fails. Sometimes they are used in conjunction with convex mirrors. Enhancement cameras are used to give more views to the problem areas. Camera positioning was based on the Field of View (FOV) of the driver. The FOV took into account the monitors and the ability for the driver to move about to see different views. The monitors could be located either in the middle or on the sides, monitor placement

was dependent on which was better for the driver to ensure optimal visibility (National 2008). Figure 2.8 shows the placements of the surrogate and enhancement cameras.

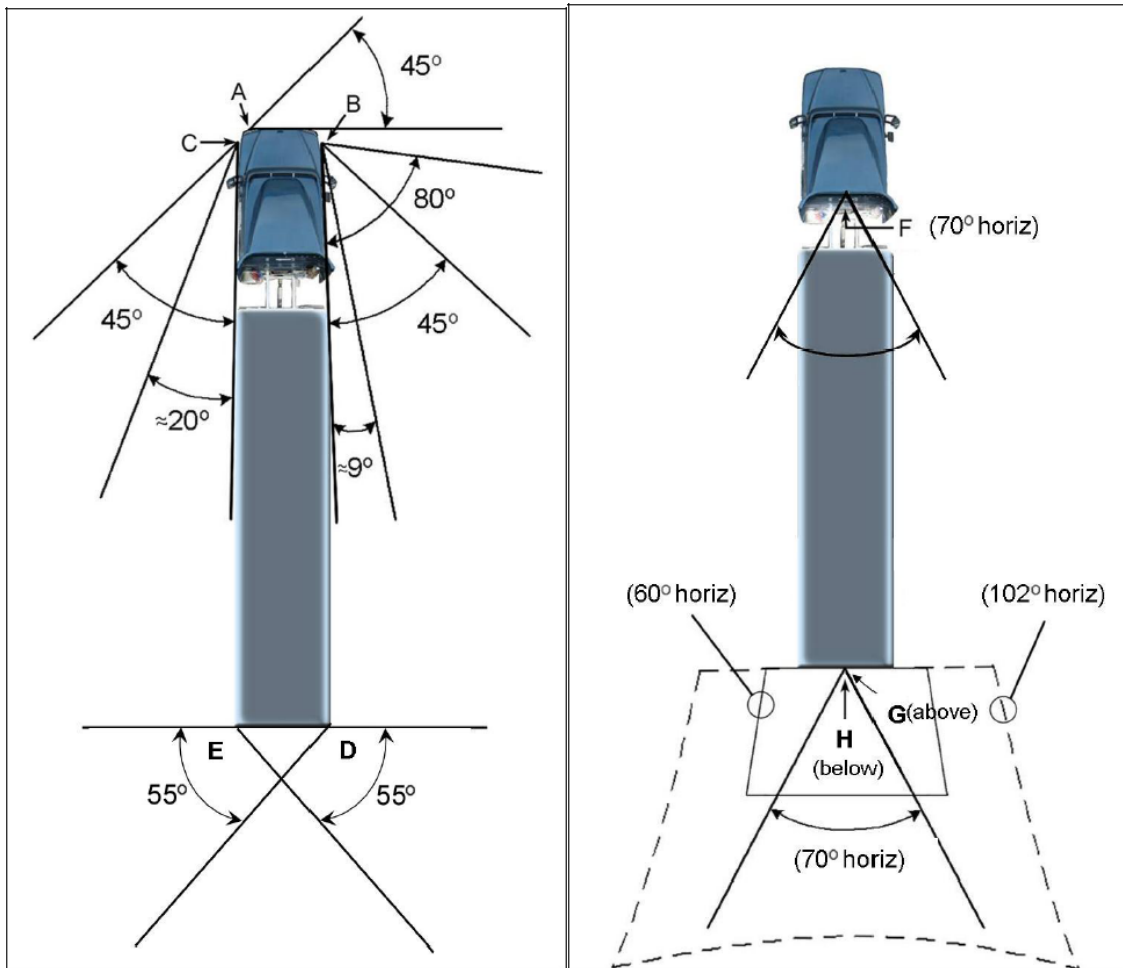


Figure 2.8: Surrogate camera placement (left) and enhancement camera placement (right). (National 2008)

## **CHAPTER 3: METHODOLOGY**

### **3.1 Proximity Warning System**

The purpose of this research is to increase work zone safety in heavy equipment operations by utilizing embedded radio frequency technology for real-time pro-active warning devices. Sensing technology will be developed that may assist ground personnel and equipment operators in detecting and recognizing hazardous environments, for example, from being too close to heavy equipment. In such an event of being too close, visual, acoustic, and vibration technology will activate alarms to the personnel through so called Equipment and Personal Protection Units (EPU and PPU). This technology will also address the lack of information on “near-misses”. It will collect data on the cause of potential collisions as a means to discovering new ways of improving the safety of a construction site.

This technology will be scientifically evaluated through the following experimental plan. First, blind spot measurements will be taken for heavy equipment found commonly in construction sites including trucks, excavators, graders and surfacing machines, semi-trucks, and standard trucks using a laser scanner as mentioned previously. Next, testing will be performed where the system is in optimum conditions; the points at which the alarm is triggered will yield the largest theoretical safety zone the system can create. Then, the system will be tested on each piece of equipment by mounting the EPU inside the cab and walking the PPU around the perimeter of the equipment and marking the points where the alarm is triggered. These measurements will be taken using a total robotic station to ensure accuracy. The safety zone may vary

for each piece of equipment due to unique mounting solutions, which alter in-cab EPU obstructions.

### **3.2 Automatic Blind Spot Calculation**

Automatic Blind-Spot Detection and Calculation tool (ABSDAC) analyzes blind spots for heavy machines used in construction. This section explains the method used for calculating blind spots and capabilities of the tool.

Laser scans of heavy construction vehicles like dump trucks, motor graders, scrapers, rollers, wheel loaders and smaller heavy equipment have been taken by mounting the laser scanner on the driver's seat. The laser scanner remotely measures the distances to all objects that are in its field of view. All recorded points (around 1.5 million; varies per scan) are registered and stored in a point cloud file. This point cloud file is later converted to a simple comma separated variable (CSV) file that has x, y, and z-coordinates of each point. This CSV file is the input to the blind spot calculation tool.

The automated blind spot calculation tool uses a ray tracing approach to calculate blind spots of any machine. The idea is to imagine a perfect light source located in place of the driver's head, and then trace the imaginary path of light emanating from the light source. If rays from this imaginary light source hit any cube that is part of the cab then it makes the area behind this cube invisible. These invisible areas are the blind spots of the machine.

### 3.2.1 Grid Representation of Machine

To compute blind spots in a sphere of radius ' $R$ ' around the machine, this volume is initially divided into virtual cubes of small size, for example, a three-dimensional grid of size  $300 \times 300 \times 300$  cubes. A sphere of 10 m radius encompassing the machine divides the grid into smaller virtual cubes of size 6.66 cm in each dimension X, Y and Z.

Based on the three-dimensional arrangement of laser range point cloud and cubical grid system, each point in the machine's point cloud data falls into one of these cubes. A grid model of the machine is built from all the points in the corresponding laser scan. Figure 3.1 shows grid model of a dump truck built from its laser scan data. All the cubes that have at least one point from the machine's point cloud are considered to build the grid model.

### 3.2.2 Ray Tracing

For implementing ray tracing in a sphere of radius ' $R$ ' around the machine, spherical co-ordinates  $(r, \theta, \phi)$  are used, starting at the location of the driver's head  $(0, 0, 0)$ . This origin is actually the source location of the laser beam of the laser scanner. In spherical co-ordinate system  $0 \leq \theta \leq \pi$  is the angle between the positive z-axis and the line formed between the origin and the point. A typical spherical co-ordinate system is shown in Figure 3.2.

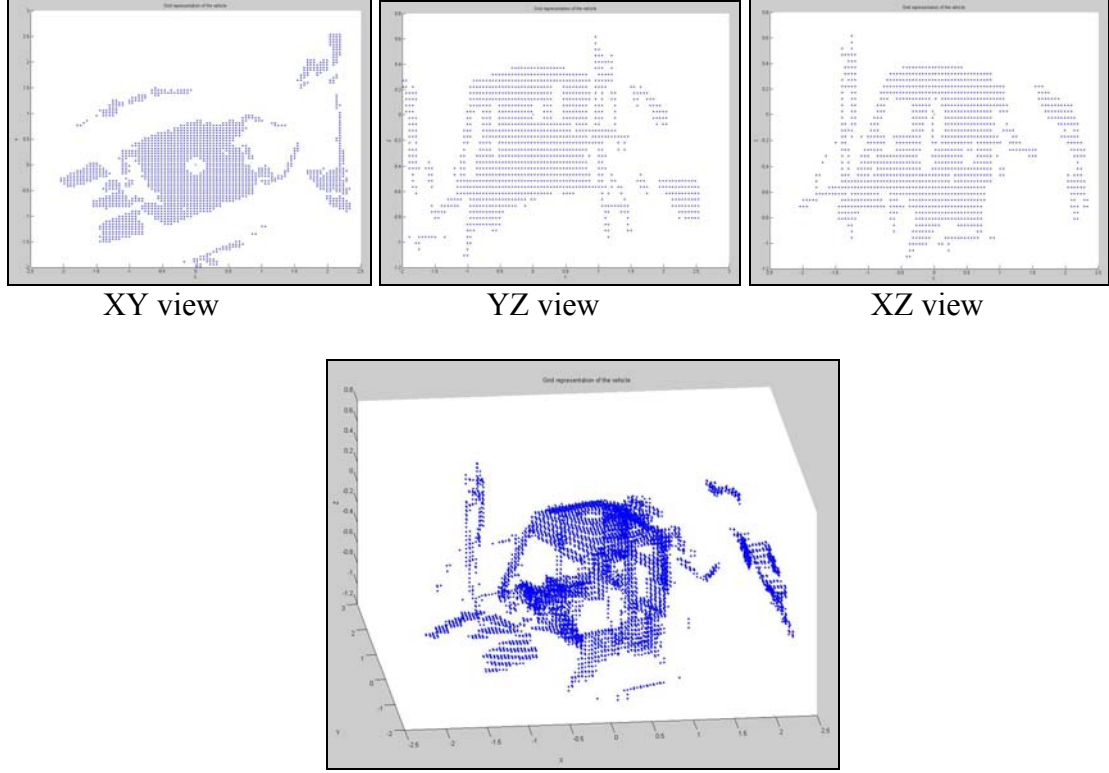


Figure 3.1: Laser scan of a dump truck converted into grid model

However, the laser scanner cannot not pick up points in the range of  $3\pi/4 \leq \theta \leq \pi$  because of the rotational restriction on the laser scanner. Also, laser scanner cannot read points that are closer than approximately 0.6 m. So, the part of roof and seat (and any other object) of the machine in the range  $0 \leq \theta \leq \pi/6$  was not captured because those points on the roof were closer than approximately 0.6 m. Figure 3.3 shows the operating limits of the laser scanner used in the experiments. The two grey regions depict the range of each view window of the scanner. Region “a” represents the front window, and region “b” represents the top window.

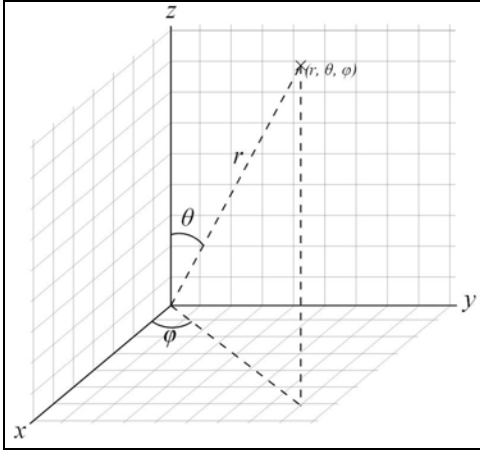


Figure 3.2: Spherical co-ordinate system

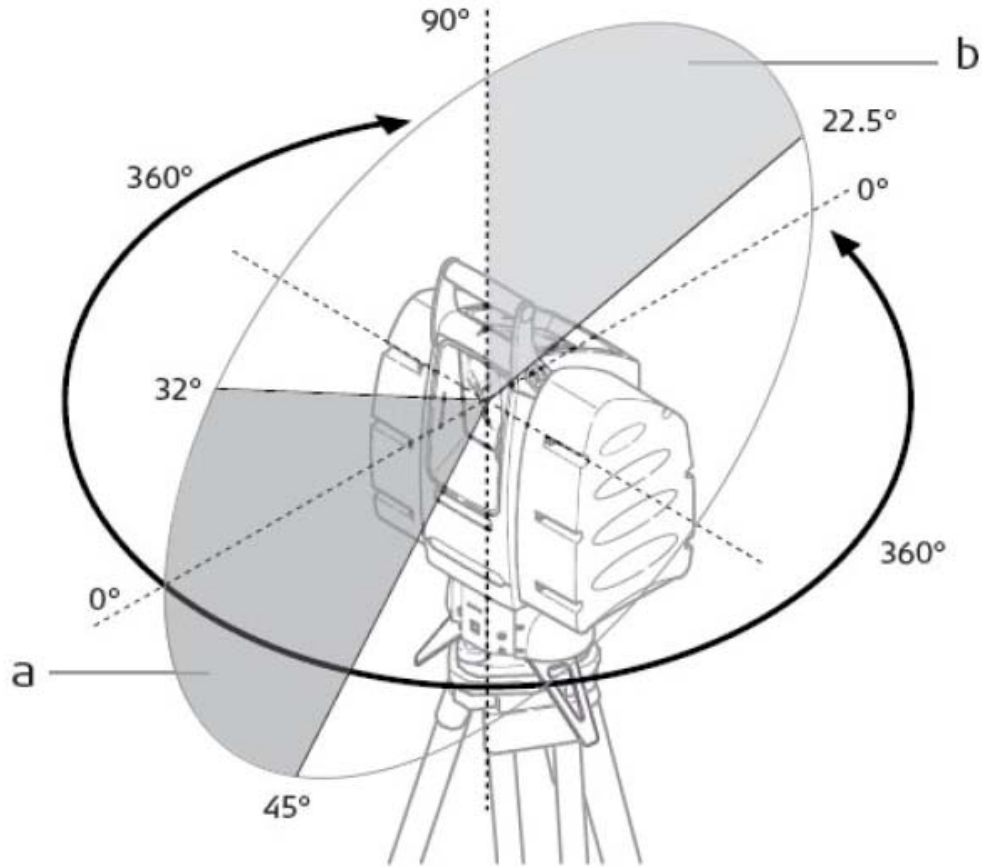


Figure 3.3: Laser scanner FOV boundaries (HDS 2006)

Because of the operating restrictions, we trace the grid starting at  $(0, 0, 0)$ , varying  $\theta$  from  $\pi/3$  thru  $3\pi/4$ ,  $\phi$  from 0 thru  $2\pi$ ,  $r$  from 0 to ' $R$ '. The following rule is applied to determine blind spots: If the trace hits a cube that belongs to machine, all the subsequent

cubes in the path of ray including this cube will be recorded as blind spots. If the ray does not hit any cube that is part of the machine, then all the cubes in the path of this ray are counted as visible cubes. Figure 3.4 shows blind spots resulting from a small square shaped plate of size 0.5 m x 0.5 m in the path of rays.

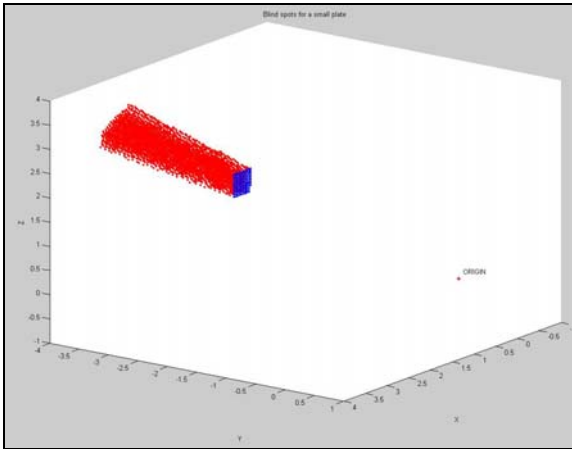


Figure 3.4: Blind spots resulting from a small plate in the path of rays

### 3.2.3 Blind Spots Statistics

A statistical analysis of the ratio of blind spots vs. visible space follows. To calculate the percentage of blind spots in the 3D grid, the number of cubes that are labeled as “blind spots”, and number of cubes that are labeled “visible” are counted. Therefore, the percentage of blind spots = number of ‘blind’ cubes \* 100 / (number of ‘blind’ cubes + number of ‘visible’ cubes).

The developed tool can also compute percentage of blind spots in a particular section of the grid. For a constant ‘k’ ( $-r \leq k \leq r$ ;  $r$  = sphere radius), the tool can be used to compute blind spots in XY plane for any  $Z=k$ , YZ plane for any  $X=k$ , and XZ plane for any  $Y=k$ . Therefore, the plane parallel to ground at the level of driver’s eyes, would be XY plane at  $Z=0$ .



To calculate blind spots in a XY, YZ or ZX plane, the number of cubes labeled as “blind spots” and cubes labeled as “visible” in that plane are counted. Therefore, the percentage of blind spots in that plane = number of ‘blind’ cubes in the plane \* 100 / (number of ‘blind’ cubes in the plane + number of ‘visible’ cubes in the plane).

#### 3.2.4 Visibility of a Person from Driver’s Perspective

Because of the blind spots of any machine, a person or construction worker standing on the ground may or may not be visible for the driver of the machine. In some situations, the person might be partially visible to the equipment operator. The tool computes percentage of visibility of a person standing anywhere around the machine. The location of the person is the input to the software.

The tool uses a user-defined cylinder model to represent a construction worker. Height and radius of cylinder can be adjusted in the tool. For general understanding, a person 1.8 m tall with a diameter of 0.6 m is considered for the experiments explained in the following sections.

Since the human eye can only see the projection of a 3D object super imposed on its retina, the equipment operator can only see the surface of cylinder. So, to calculate percentage blind spots of the cylinder, the percentage of surface of cylinder that is not visible to the equipment operator has to be calculated. To accomplish this, when ray tracing is performed, only cubes on the surface of cylinder are considered. After ray tracing is performed, we will have cubes on surface of cylinder that are visible and cubes on the surface of cylinder that are marked blind. This can be used to find out percentage of visibility of the cylinder. Percentage of visibility of cylinder = number of blind cubes

on the surface of cylinder \* 100 / (number of blind cubes on the surface of cylinder + number of visible cubes on the surface of cylinder).

Figure 3.5 shows different views of the cylinder's surface analyzed for blind spots. This is the analysis of a person standing on ground (which is approximately -3.29 m from the location of the laser scanner for the dump truck) at  $x = -4$ ,  $y = -4$ , and  $z = -3.29$ . The area in green is the visible region and the area in red is marked as blind spots.

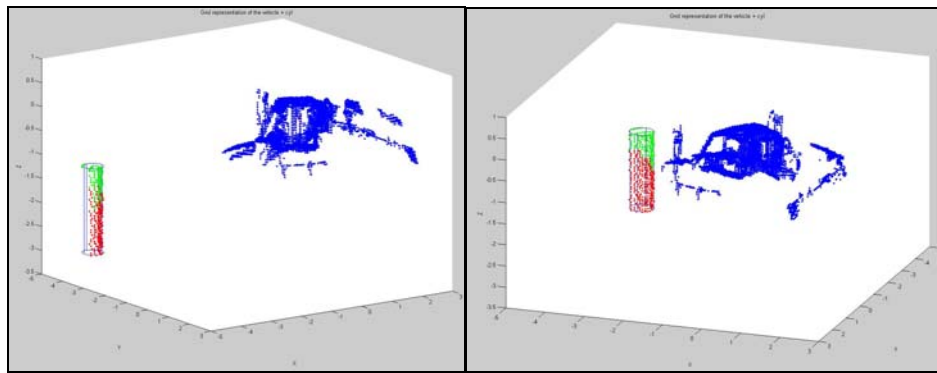


Figure 3.5 a

Figure 3.5 b

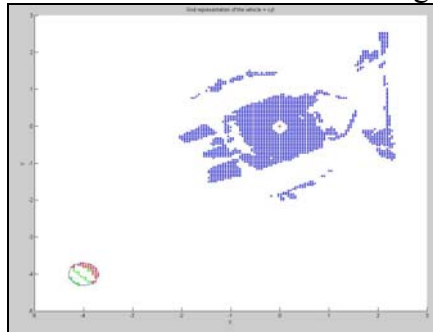


Figure 3.5 c: Plan View

Figure 3.5: Visibility of a person standing on ground at  $x = -4$ ,  $y = -4$ ,  $z = -3.29$

## **CHAPTER 4: EXPERIMENTS & RESULTS**

### **4.1 Technology Used**

The system employed in this research uses active RFID technology and is comprised of an in-cab device and a hand-held device. The in-cab device contains a single antenna, reader, and alarm; this part is called the Equipment Protection Unit (EPU). The hand-held device contains a chip, battery, and alarm; this part is called the Personal Protection Unit (PPU). The EPU sends out a signal from the antenna in a radial manner, and loses strength the further away the signal gets from the EPU. The PPU then intercepts the signal at approximately 61 meters on average in ideal conditions; once this occurs the PPU automatically returns the signal such that both systems trigger their internal alarms. The operation of sending and receiving information is instantaneous; the whole process occurs in real-time. Figure 4.1 shows the EPU, and Figure 4.2 shows the PPU worn by one of the experimenters. The small PPU can be worn on the side of the arm or on a belt. The system is durable and wearable; the casings are sturdy and can stand up to the daily weathering that occurs on the construction site. The audible alarm that occurs on both the EPU and PPU is of sufficient strength to notify personnel and is a different sound than any other sound that is present on a work-site. The PPU has a vibrating alarm also so that workers can be notified even if wearing headphones or working in an area with lots of noises. The EPU has a visual alarm along with the audible alarm for the same reasons, to alert operators even if they are working around lots of noises. The EPU is compact and can fit into the cab of a vehicle without causing any obstructions visually or mechanically.



Figure 4.1: Equipment Protection Unit (EPU) prototype



Figure 4.2: Personal Protection Unit (PPU) prototype

## **4.2 Results of Blind Spot Measurement**

The blind spots of common construction equipment including, but not limited to, excavators, rollers, dozers, dump-trucks, and cranes, may be determined through the use of 3-D laser scanning. A complete 360-degree laser scan of each piece of equipment will be collected, and each completed scan will yield a virtual model, in which anyone can navigate around on a computer. The scans taken are of equipment as they are in the construction field; it is common on construction sites for equipment to be altered by the contractor, owner, or equipment operator to their needs. For that reason, the laser scanner was needed to gain a pictorial representation of the equipment as it is used in the construction industry in real situations. These 3-D models will aid in determining all blind spots (direct and indirect) of the equipment in different types of scenarios and poses, including operator height differences. Direct line-of-site is what the operator can see in front of him/her without the use of cameras or mirrors. When direct line-of-site is blocked it is termed a direct blind spot. An indirect blind spot is an area of visibility that is obstructed even with the use of cameras or mirrors. Once these blind spots have been determined, the necessary safety zone can be established for each piece of equipment. The safety zone is the area in which an alarm sounds, alerting both the operator(s) and worker(s) that the safety zone is breached, and a collision is probable (Fosbroke 2004).

#### 4.2.1 Manual Calculation of Blind Spots

Figure 4.3 shows the blind spots of the off-highway dump truck in plan view within a 15 m radius around the equipment. Figure 4.1 also shows the regions visible by the mirrors, indicated by the hatched areas.

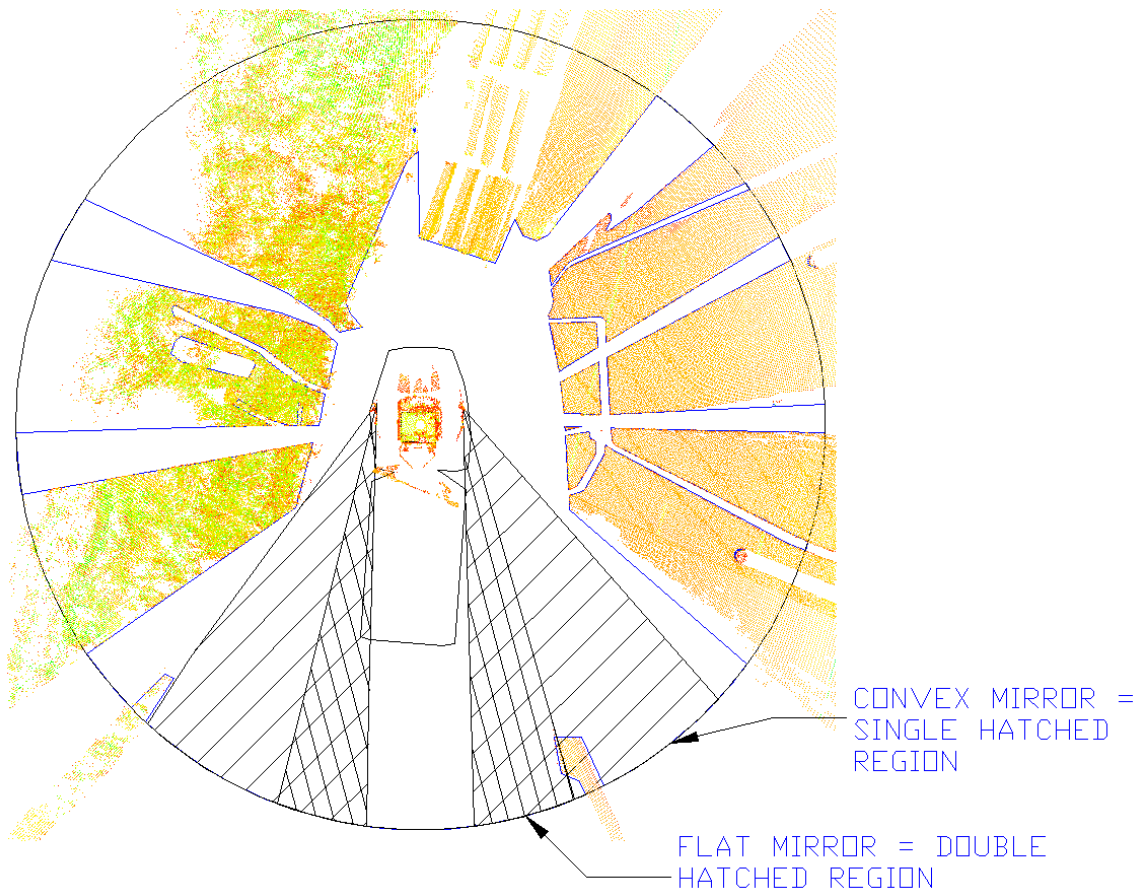


Figure 4.3: Laser Scan data of blind spots with visible regions from mirrors at 15m

The effect of “articulation” about a pivot point may cause reduction of possible visible regions by mirrors in heavy equipment. The dump truck is in fact an articulating dump truck, in which the pivot point is behind the cab of the equipment, when the vehicle is turning, will most likely inhibit the view visible to the operator in the mirror(s). In this case, convex mirrors may assist the operator. The blind spots of the off-highway truck

were determined for actual site conditions during the scan. The process to determine the blind spots of equipment are as follows:

1. Laser Scan Image: Acquire laser scan of the equipment (inside cab)
2. Cab geometry and Field-of-View (FOV): Analyze for cab geometry using laser scanner point-of-view (POV), POV can be moved in the virtual environment that is created
3. Blind spots: Use CAD (computer-aided drawing) program to manually draw actual blind spots in plan, side, and front views
4. Indirect blind spot: Views in the blind spot measurement from Step 2 that become visible when using equipment mirrors, are manually recorded using a robotic total station (RTS). The RTS is located behind the vehicle, once a person appears in the blind spot, the equipment operator manually records the person's position
5. Final diagram of blind spots: The direct and indirect blind spots are overlaid to determine the ratio FOV vs. blind spots

Table 4.1 displays the results for four pieces of equipment. Table 4.1 shows the direct blind spots in the first three columns; displaying the FOV for front, side, and plan views. The next columns show the increase in FOV and decrease of blind spots when the mirrors are used, this value is a negative value. The final column displays the net value of blind spots when combining the direct blind spots and the subsequent aid that mirrors bring. The dump truck uses convex mirrors in addition to flat mirrors while the roller uses only flat mirrors. Laws in United States require that the rear view and side driver mirror have

flat mirrors in addition to the optional convex mirrors because of the distortion that convex mirrors cause. However, it is allowed that the side passenger mirror be a convex mirror alone.

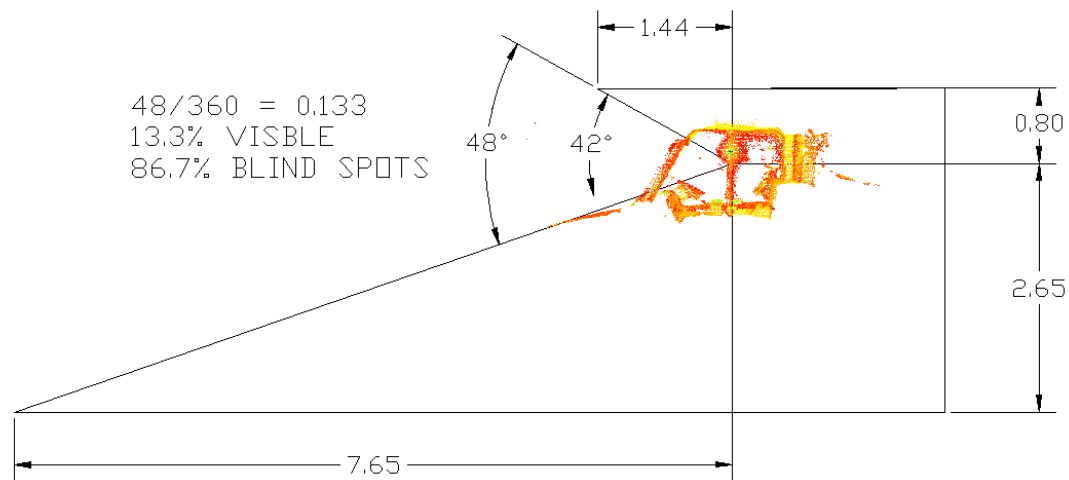
Table 4.1: Tabular Results for Blind Spot Percentages for Equipment

		BLIND SPOTS (%)						
		No Mirrors			Mirror Improvement			Net
	View	Plan	Front	Side	Plan			Plan
	Mirror Type				Flat	Convex	Overall	
Equipment	Dump Truck	49.91	86.7	72.78	-7.84	-12.56	-20.4	29.51
	Roller	27.92	62.5	71.67	-4.38	N/A	-4.38	23.54
	Motor Grader	51.44	67.1	71.03	N/A	-6.96	-6.96	44.48
	Excavator	52	65.6	75	-2.05	-0.7	-2.75	49.25

All experiments were done in real construction scenarios; therefore there were a number of obstructions surrounding the equipment that caused discrepancies in the blind spot measurements. Figure 4.3 shows this observation; the plan view displays the front of the cab with an indent where there would typically be a blind spot. The obstruction in front of the dump truck was large enough to be seen even with the blind spots present in the front of the cab; if this obstruction had been vertically smaller than it would have been in the blind spot and the laser scanner would not have been able to take an image of it and there would be no “dent” in the results. Furthermore, the topography of the surrounding ground (hills, etc.) is a contributing factor affecting the results from the laser scanning. The further the object is away from the equipment the more FOV the operator has, allowing the operator to notice the obstruction – this explanation is the reasoning behind the “dent” in the dump truck results mentioned above.



Figure 4.4 shows that the off-highway dump truck has about 87% blind spots in the side elevation view. This equipment was chosen because of its large use on a construction site and the amount of blind spots it has present. Statistics have shown that trucks have one of the largest incident rates for fatalities in contact collisions (CFOI). Figure 4.5 shows there are about 73% blind spots in the front elevation of the off-highway truck.



NOTE: DIMENSIONS ARE IN METERS

Figure 4.4: Side Elevation of blind spots of Off-Highway Truck

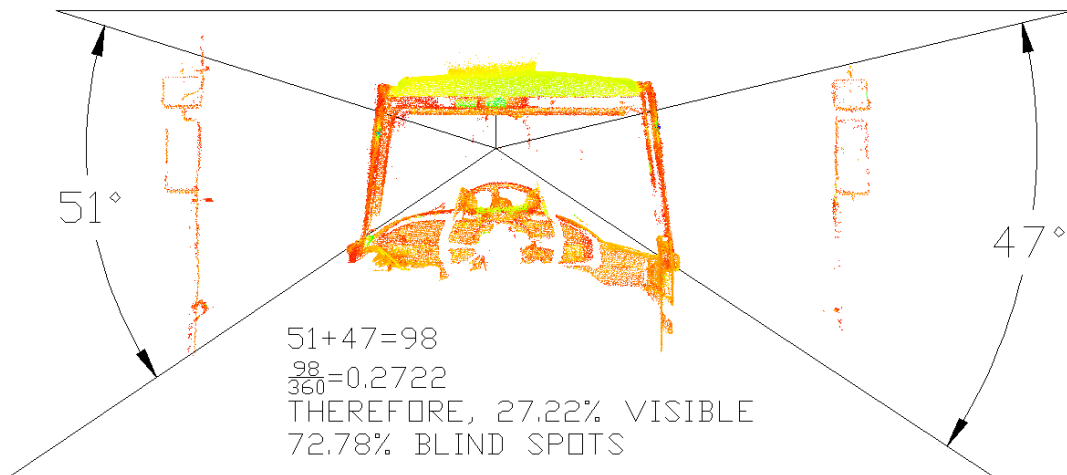


Figure 4.5: Front Elevation of blind spots of Off-Highway Truck

The following results show that the proximity warning device does not allow “close” collisions, preventing interaction between worker and equipment, and vice versa. The analysis in Table 4.1 shows the difference in blind spots for various heavy equipment and the different needs that are present when working around various types of equipment. The proximity warning device is aimed to work with these changes and adjust accordingly.

#### 4.2.2 Automatic Calculation of Blind Spots

Two computer tools were developed within the automatic blind spot calculation program, one to compute the planar percentage of blind spots and one to compute the 3D volume percentage of blind spots and the percentage visibility of a person standing in proximity to heavy equipment.

#### 4.2.2.1 Experiment 1

In this experiment, the percentage of blind spots in the XY plane is calculated by varying the radius of sphere encompassing the vehicle. This percentage of blind spots is the percentage of area on ground that is invisible to the driver of the machine. Figure 4.6 shows blind spots on three planar levels (ground, 1.5 m tall person, and operator eye level) for a bulldozer at a radius of 10 meters. The areas in blue are the invisible areas on each level, and the white areas are visible to the operator. The red points are an overlay of the laser scan data points used in the computer tool to create the blind spots on top of the blind spots, in the same orientation. The blue outer circle depicts the boundary region for each plane of the area analyzed by the computer tool. Figure 4.7 shows the manual calculated blind spots of the dump truck with radius 10 m. Figure 4.8 shows the blind spots for a standard regular cab truck as determined by the computer tool. Figure 4.9 shows the blind spots of the manual comparison of the truck.

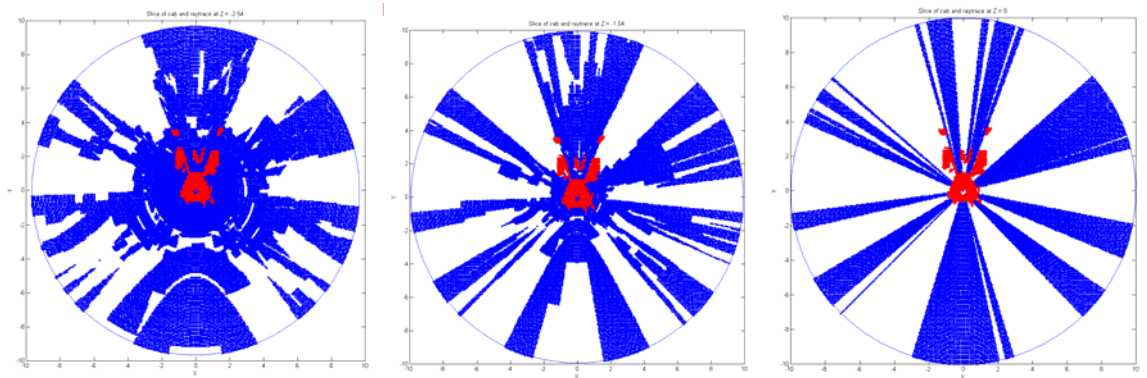


Figure 4.6: Blind spots of bulldozer with 10 m radius: (left to right) ground level, 1.5 m tall person, operator eye level (see Appendix A for full figures)

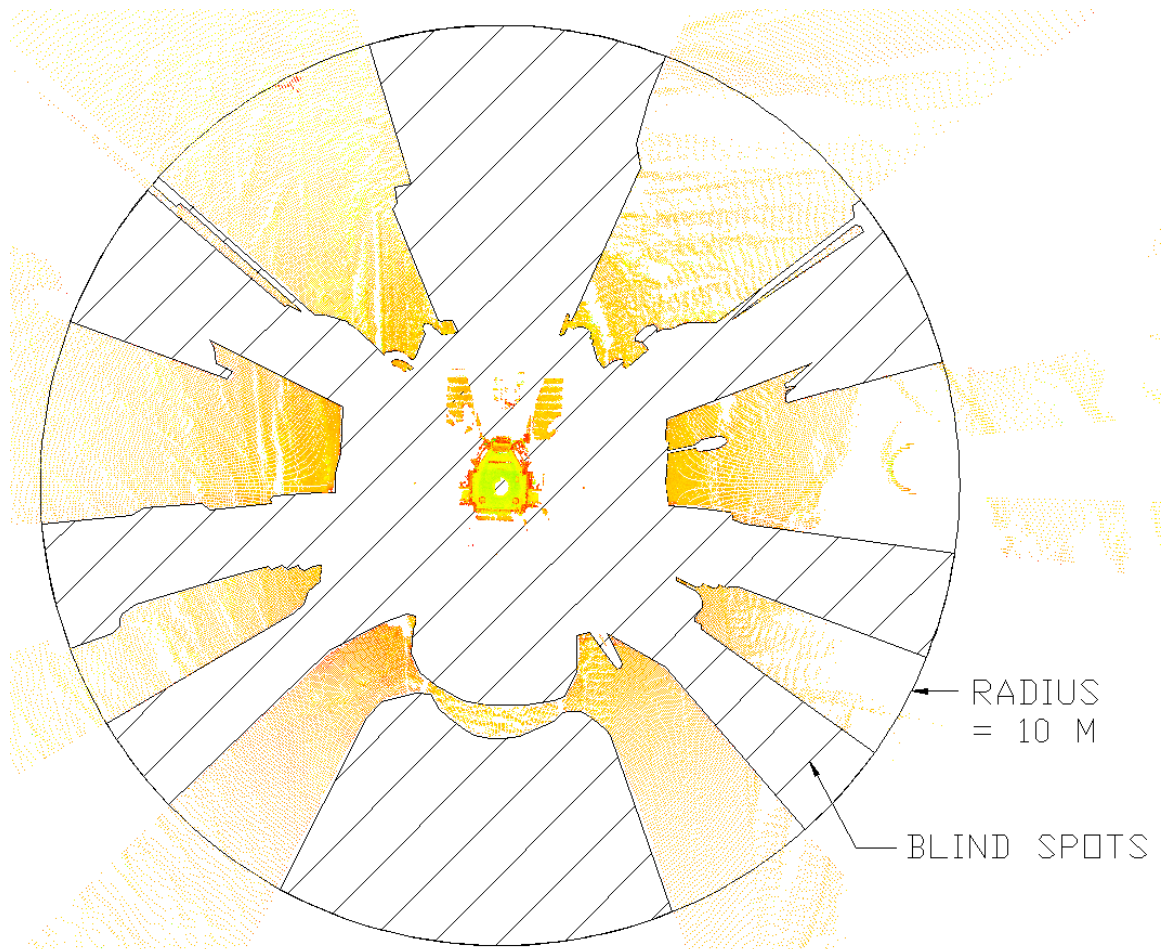


Figure 4.7: Bulldozer manual blind spot calculation in AutoCAD using laser scan “modelspace”, hatched region represents blind spots

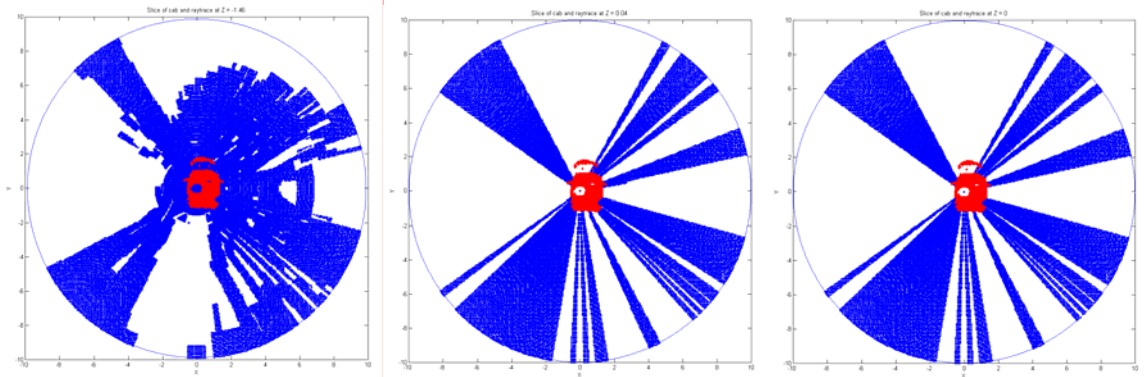


Figure 4.8: Blind spots of truck with 10 m radius: (left to right) ground level, 1.5 m tall person, operator eye level (see Appendix A for full figures)

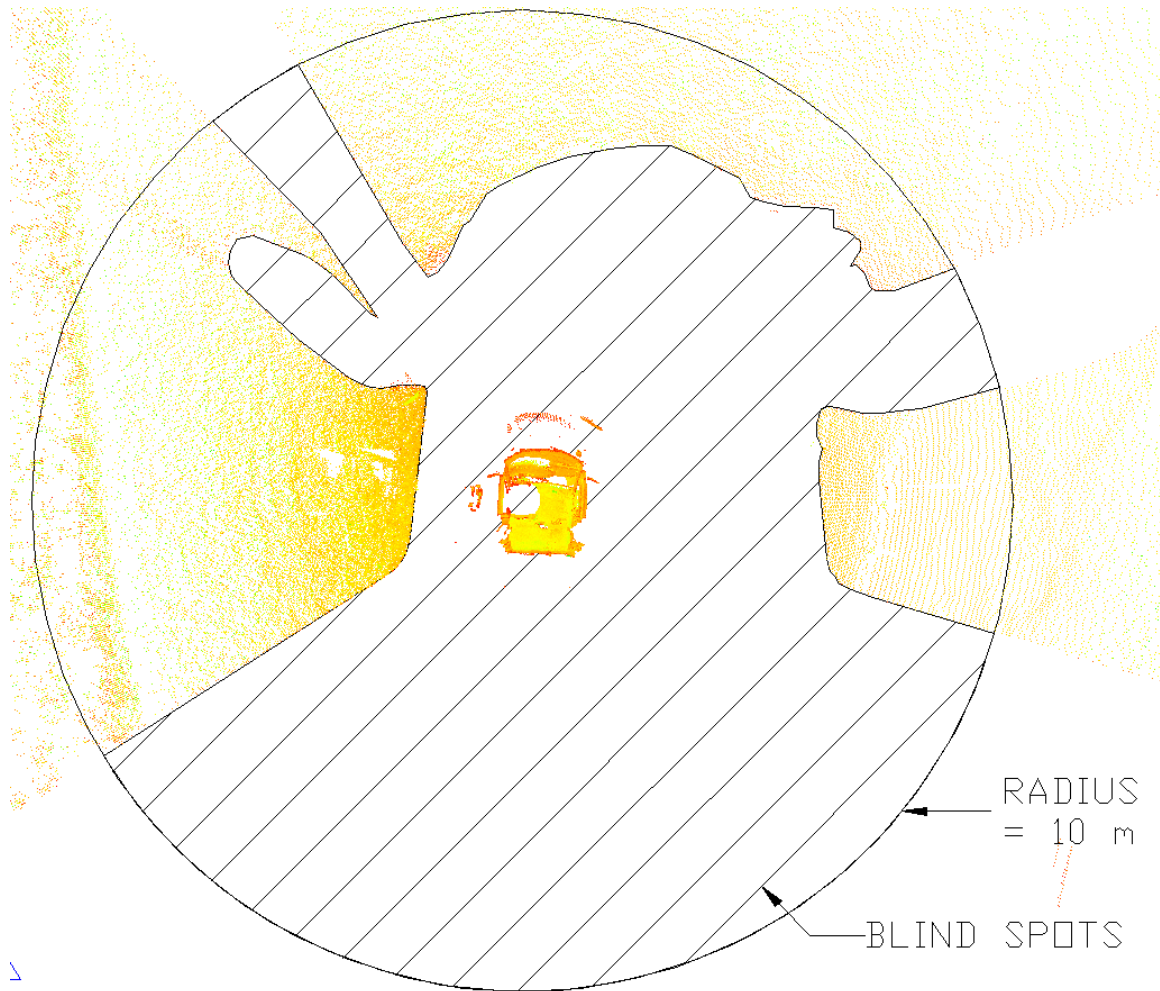


Figure 4.9: Pick-up Truck manual blind spot calculation in AutoCAD using laser scan “modelspace”, hatched region represents blind spots

The results are similar to Ruff’s (2007) and Hefner’s (2003) experimental results, but the automatic method is new and more efficient because it is capable of providing multi-view reference frames and multiple planar comparisons without the manual effort. Like Ruff’s experiments, the ground plane and the 1.5m-high and 1.8m-high planes (with respect to the ground plane) are analyzed and compared to depict the differences in the blind areas for objects and people. The field-of-view of the scanner is shown in Figure 3.3; the default origin of the point file is the location of the scanner, but the location of the ray trace may be modified in the computer tool. All results included were calculated with the default origin established in the computer tool. Reasons for creating such

functionality in the program may be to account for the operator's ability to translate in the x-, y-, or z-axis his/her head about the cab of the equipment. And because of the mentioned FOV limitations of the scanner, the results shown assume "solid roofs and solid floors". The distance limitation of the scanner (approximately 0.6 m) results in "imperfections" in the scan, which may be translated to the computer tool. These imperfections include objects to be scanned are too close, objects scanned do not reflect sufficient light for recording points, and direct laser refraction off of windows (surface scanned is perpendicular to the laser beam). Dirty windshields may reflect scan points off of the windshield instead of going through the window and recording a point on the ground. A clean windshield is very important for the operator's visibility. Figure 4.10 shows a dirty windshield versus a cleaned windshield in the computer tool; the scanner computer program easily allows the removal of "noise" data points, but the addition of "value-added" points is not possible in the scanner's computer program, which is separate from the computer tool developed to analyze the blind spots. Table 4.2 shows the percent of blind spots results of the computer tool developed for planar measurements for all equipment analyzed. Two radii were chosen (10 m and 15 m) to provide comparison in the results.

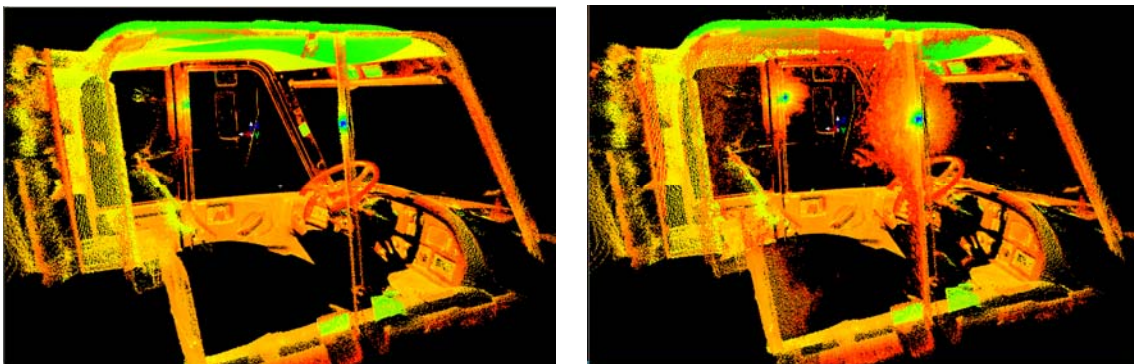


Figure 4.10: Clean (left) and dirty (right) windshield comparison

Table 4.2: Percent Blind Spots, Automatic Computer Tool

			% Blind Spots (R = radius)	
			Computer Tool	
	z-value	Description	R = 10 m	R = 15 m
Bulldozer	0	Eye-level	36.97	46.54
	-0.74	1.8 m Tall	44.24	54.31
	-1.04	1.5 m Tall	46.60	56.38
	-2.54	Ground	61.06	64.02
Pick-up Truck	0	Eye-level	37.91	40.99
	0.34	1.8 m Tall	33.08	39.26
	0.04	1.5 m Tall	37.93	41.16
	-1.46	Ground	53.63	47.68
Dump Truck	0	Eye-level	28.45	31.17
	-1.49	1.8 m Tall	48.82	49.93
	-1.79	1.5 m Tall	52.06	50.64
	-3.29	Ground	71.08	61.89
Roller	0	Eye-level	20.43	23.77
	-0.79	1.8 m Tall	25.17	29.99
	-1.09	1.5 m Tall	28.47	31.38
	-2.59	Ground	48.73	41.89
Excavator	0	Eye-level	40.71	45.99
	-0.77	1.8 m Tall	46.74	45.88
	-1.07	1.5 m Tall	48.74	46.43
	-2.57	Ground	63.77	56.42
Motor Grader	0	Eye-level	27.22	34.81
	-0.88	1.8 m Tall	46.32	45.96
	-1.18	1.5 m Tall	48.55	50.36
	-2.68	Ground	68.45	63.47

Manual calculations were completed for three equipments; Table 4.3 shows the results. Since the actual scan data is analyzed in a CAD program by hand, only one “plane” from the top view is observable.



Table 4.3: Percent Blind Spots, Manual Calculation

	Blind Spot Manual Calcs. in AutoCAD (%)	
	R = 10 m	R = 15 m
Bulldozer	58.42	53.74
Pick-up Truck	63.69	52.48
Dump Truck	62.98	49.91

#### 4.2.2.2 Experiment 2

In this experiment, the percentage of visibility of a person on the ground is calculated by varying the distance from the machine in any chosen location. It was observed that as the person moves closer to the machine, the visibility of the person decreases. This computer tool allows the opportunity to visualize which locations around equipment are more dangerous than others; though it makes “perfect sense” to infer from Experiment 1 that a person who is 1.5 m tall will not be visible in the blue areas of the 1.5 m plane diagram, thus allowing the assumption of classifying that area as “dangerous”. This approach is completely new and additional to the traditional blind spot measurements from Ruff, Hefner, and other researchers alike.

As mentioned in the methodology, the laser scanner has limitations in recording points and its scanning FOV (field-of-view). For example, figure 4.11 shows a screenshot of the computer interface of the laser scanner for the scan of the bulldozer’s floor. Notice that there is a circle “missing” in the data points, this exemption is due to the limitation of the scanner – can only scan from the horizontal (level with the ground) down to -45 degrees. Also in figure 4.11, notice the missing points in the top portion of the seat and the direct laser refraction off of the back glass windshield; both scan characteristics must be accounted for when reviewing the results of the automatic blind spot calculations in the computer tool. Figure 4.12 shows the same scan, but the view of



the roof – a portion of the cab roof is too close to the scanner to be recorded. The position of the scanner may not be lowered, because the aim of the research is to scan the cab at the most likely position of the operator’s eye level.

Using this methodology, “noise” data points were removed from the windows of the cab, and then created the CSV file. The 3D volume part of the computer tool accommodates for the scan “imperfections” with user-inputs: top vertical angle for the bulldozer was chosen as 35 degrees and zero percent of the “top cone” is visible, because the roof exists. The bottom vertical angle is always 45 degrees (scanner boundary), and in the bulldozer case zero percent of the “bottom cone” is visible. Furthermore, the imperfections caused by the seat and other objects with surfaces unable to record points (often the posts of the roof support for the cab of the vehicles) are accounted for by an estimation of “percentage of additional blind spots” to add back to the computer results. This estimation is performed using the “grid” in the laser scanner interface; horizontal and vertical lines represent the degrees of the scanner’s FOV. There are 360 degrees in a circle, so dividing a sphere horizontally and vertically provides  $36 \times 36 = 1296$  grid boxes. The estimated number of grids that “should” be present to create blind spots are totaled and divided by the total number of grid boxes (1296). This formula provided the result of approximately 2.5% additional blind spots areas to add back to the calculated blind spots in the computer tool – this addition is programmed into the computer tool.

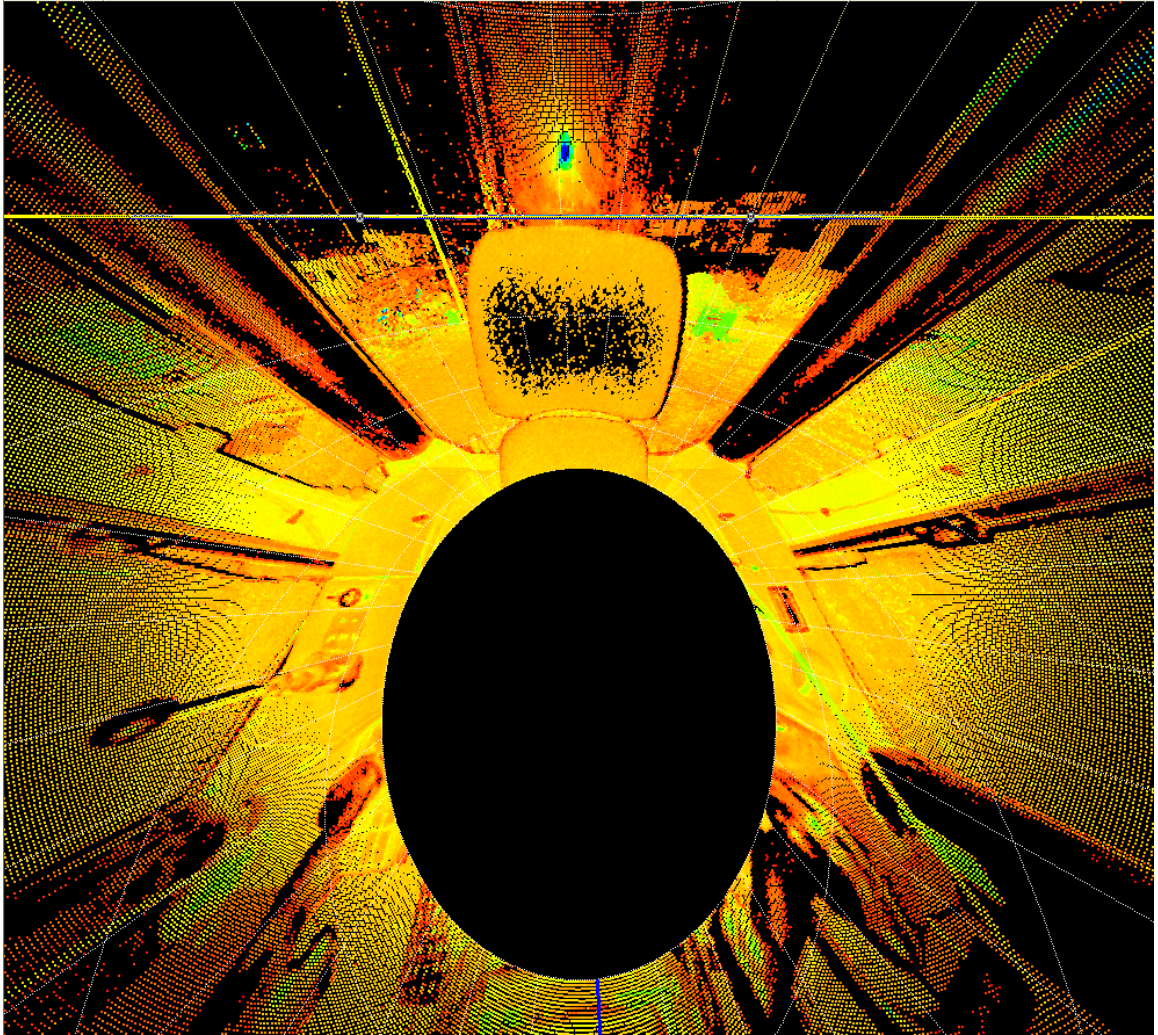


Figure 4.11: Bulldozer floor view of laser scan computer interface

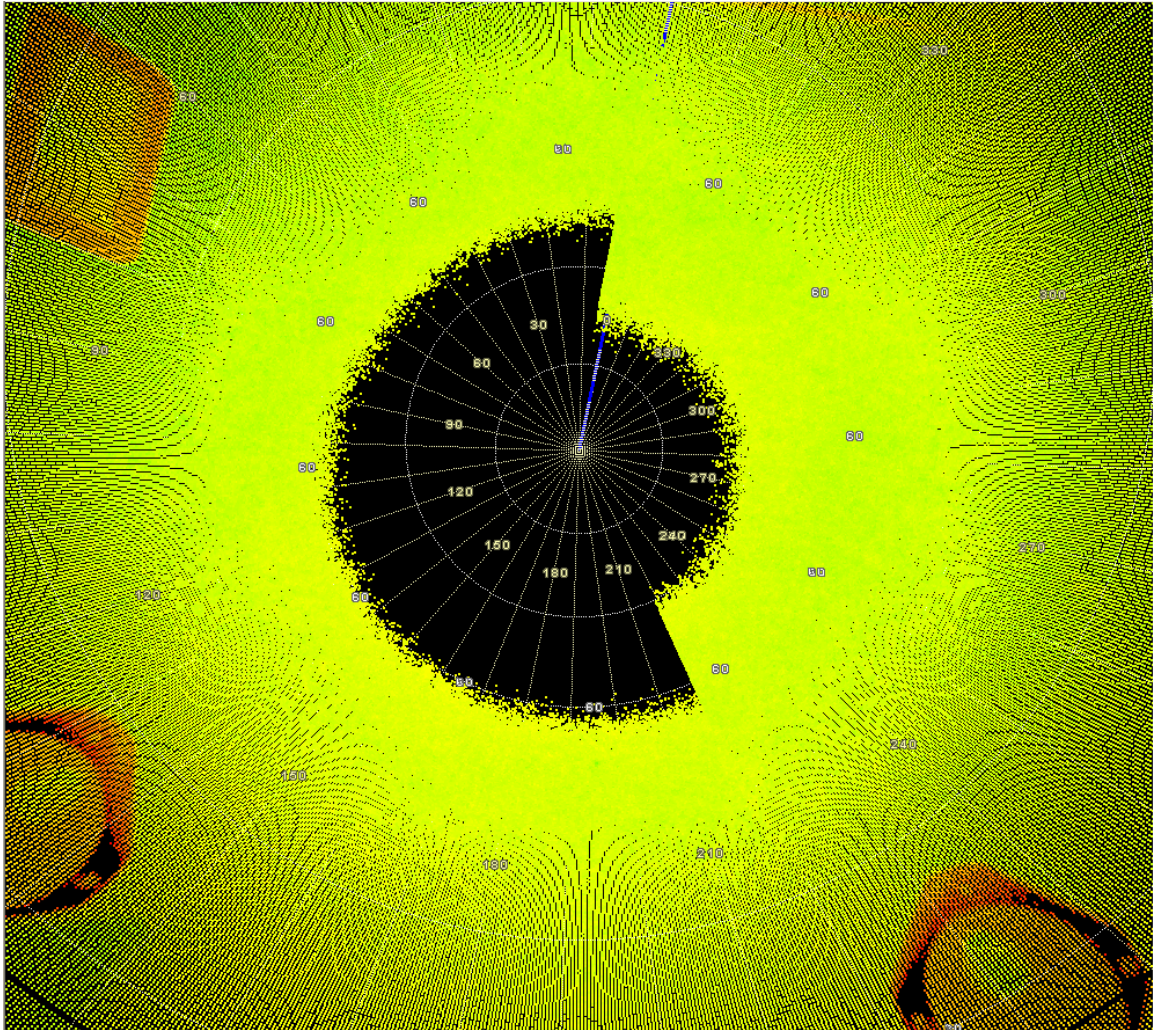


Figure 4.12: Bulldozer roof view of laser scan computer interface

Figure 4.13 shows the plan view of the laser scan for the bulldozer, with concentric circles centered at the origin. The radii for the circles are 2.5 m, 5 m, and 10 m, respectively. The three straight lines drawn represent the chosen paths to measure the visibility of the 1.8 m tall, 0.6 m wide person. Notice the positions A-C, E-G, and I-K; these letters represent the positions chosen for the worker to “stand”. Position E is likely not to occur, because the person would be run over in this position; E was kept in the layout to keep the format the same between all the trials. The imperfections in the CSV file still exist, but are accounted for as best as possible with current knowledge.

Table 4.4 shows the results for this method. Notice that position B has many visible data points, therefore “B” is visible from the cab of the bulldozer. Going to C from B you would think that the visibility should increase, but the visibility of the person actually decreased from 98% to 87% visibility. This decrease may be due to objects on the construction site, or mounted objects in the bulldozer cab, and a host of other possibilities. However, notice that there fewer visible data points at point C in Figure 4.13. And at locations such as G and K, the person is not visible at all. Therefore, the manual drawing corresponds to the computer tool’s results. Figure 4.14 shows the 3D image of the computer tool calculation for position C.



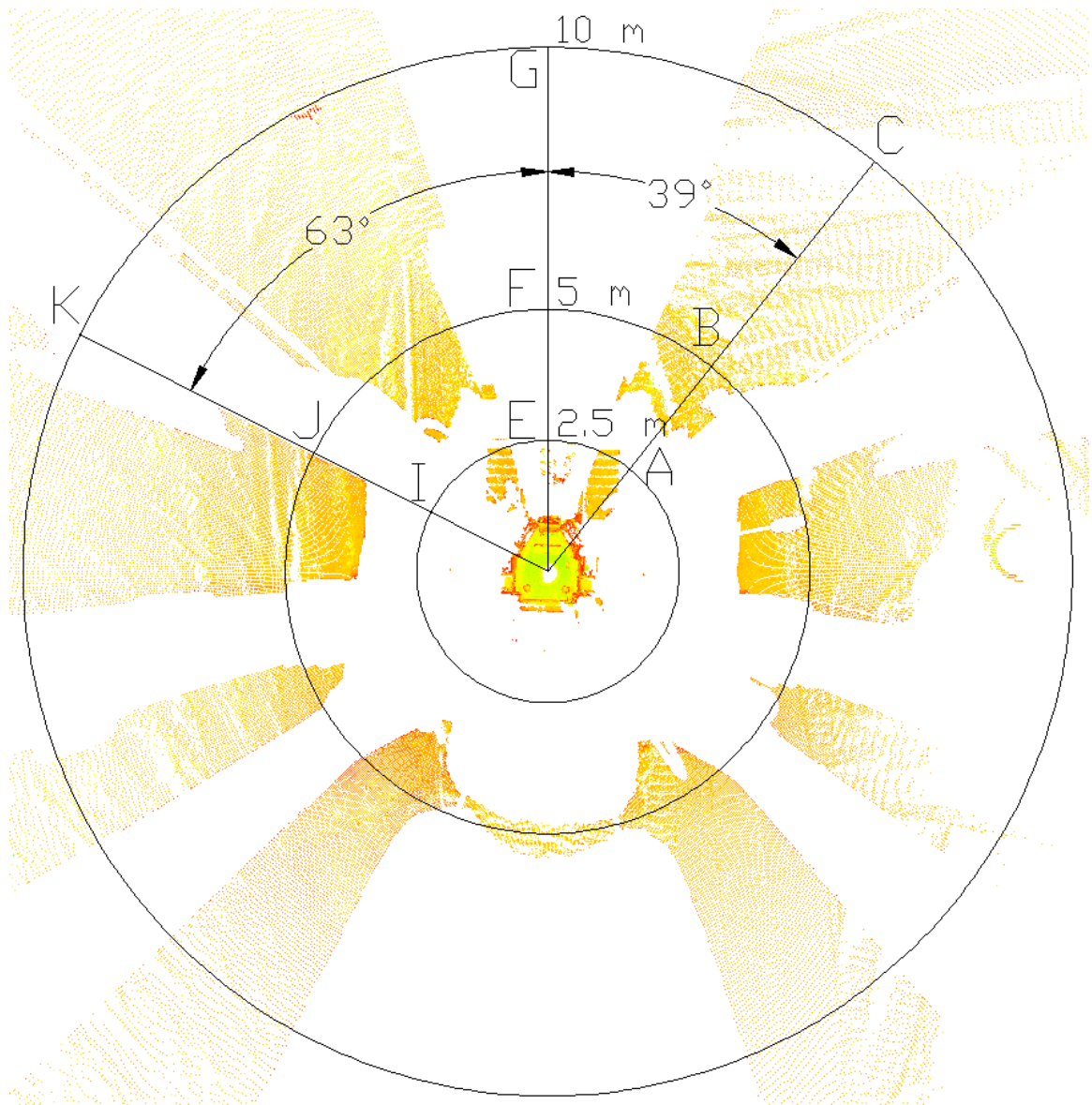


Figure 4.13: Computer method coordinate layout for bulldozer

Table 4.4: Percent visibility of person per location

Position	x-coor.	y-coor.	% Visibility of Person
A	1.5575	1.9556	43.0857
B	3.115	3.9111	98.1481
C	6.23	7.8222	87.1429
E	0	2.5	5.23446
F	0	5	3.86847
G	0	10	0
I	-2.2298	1.1305	23.5597
J	-4.4596	2.2609	23.5189
K	-8.9193	4.5218	0

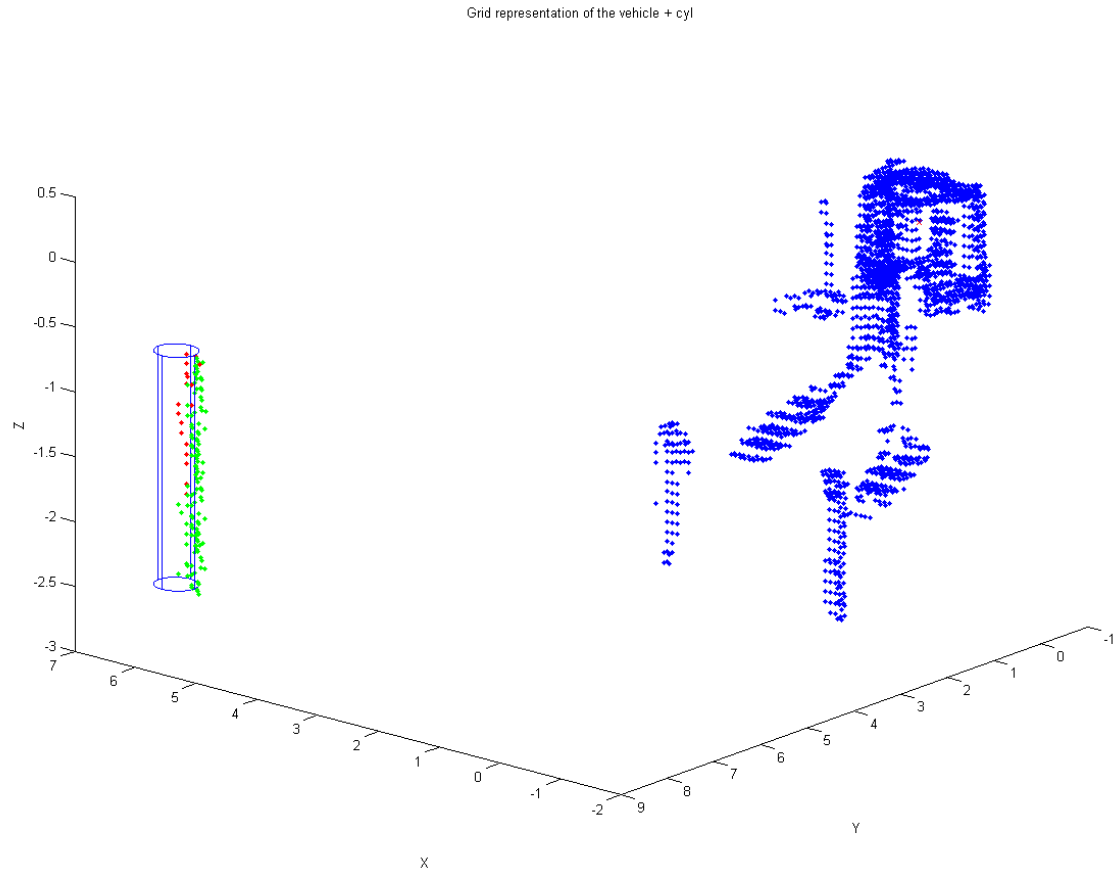


Figure 4.14: Percent visibility of person at location C

### 4.3 Development of Proximity and Warning Device

From the background information and blind spot measurements the safety needs of the construction site were discovered and a prototype safety device was derived. The following stages were undertaken to develop the device.

#### 4.3.1 Stage 1 – Preliminary Laboratory Testing

Laboratory like conditions were created to initially test the prototype. The tests were done outside on clear days in open areas mostly free of obstruction at a radius of 80 meters; after 80 meters there were mild obstructions. A one-second Robotic Total Station (RTS) was used to take distance measurements. The RTS records the distance at which

the EPU and PPU both alarm. The RTS was placed in the center of the field along with the EPU, and a tester walked around with the data collector and PPU. The following steps were taken to test the technology:

1. Reference frame (zero degree azimuth) established on the RTS.
2. Tester starts on zero azimuth about 80 m away from the reader.
3. Tester walks toward the apparatus, holding the tag in front of him/her, while also holding the prism rod for the RTS.
4. Tester stops walking when EPU “reads” the PPU and alarm sounds.
5. Tester records the distance from the EPU to the PPU.
6. Tester moves to the next “degrees” checkpoint (every 10 degrees around the apparatus to form a “complete circle”).

This process was followed to establish a base perimeter around the EPU, before any obstacles were put into place. The manner in which the EPU would be placed on the equipment and the PPU would be placed on the worker was also determined for use in stage 2. Figure 4.15 shows the results of the ideal condition overlaid on the construction like conditions, the ideal conditions showed an average radius of 61 meters. It was observed that the PPU alarm sounded prior to the EPU alarm sounding, this was the first warning alarm to alert the ground personnel that they were approaching a dangerous situation. The distance recorded during testing was a closer distance at which the EPU’s and PPU’s alarms sounded simultaneously and warned all involved personnel of the danger.

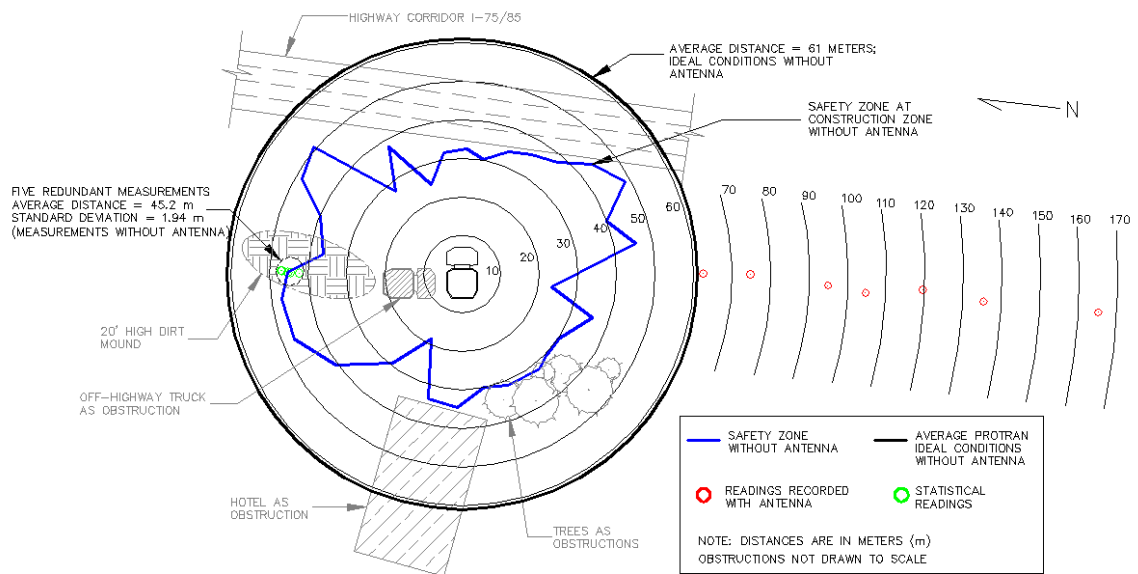


Figure 4.15: Spider-map of Safety Zone for PPU around EPU

#### 4.3.2 Stage 2 – Preliminary Harsh Field Condition Testing

The system was then tested in field like conditions; harsh construction settings with equipment and obstacles were used to mimic the day-to-day setting in which the device was intended to be used. Equipment was kept stationary but was set in close proximity of materials, other equipment, and lab personnel acting as workers. The EPU was set inside the cab of the equipment and the PPU was placed on a person. The technique used to take measurements of the alarm sounding was the same technique used in Stage 1, except the checkpoints were at every 30 degrees instead of 10 degrees.

The proximity warning device was tested on a forklift, excavator, dozer and dump-truck. The EPU was placed inside the cab of the equipment. Figure 4.16 displays the results obtained from the proximity warning device testing on the excavator and dozer. The grey area is the unsafe zone, the generalized blind spots area – the area in



which the alarm must sound. Since the EPU emits a signal in a radial manner, the blind spot measurements are condensed down into a circle that shows the general, and most dangerous area, for the worker to be in. Outside that area the worker is in the safe zone. The orange lines represent the points where the proximity alarm sounded. The worker never entered into the unsafe zone.

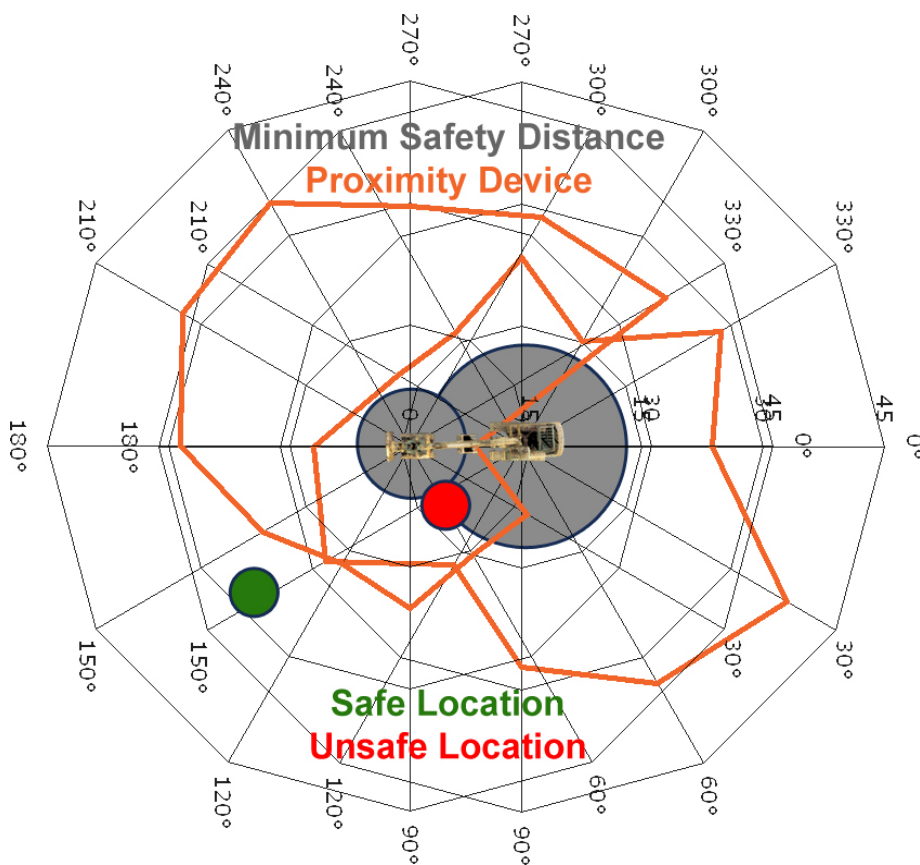


Figure 4.16: Active proximity warning zone

A field trial on an off-highway truck is shown in Figure 4.15. At the arbitrary 270 degree angle during the experiment, five redundant measurements were recorded, and Table 4.5 has statistical results on the reliability of the EPU and PPU; average distance

read was 45.17 meters, and the standard deviation was 1.94 meters. Additionally, we added the optional antennae to the EPU, which boosts the signal, and recorded a maximum read distance of about 165 meters. Figure 4.15 displays the results obtained from the truck experiment; the solid line is the results from the construction like settings. This construction site was adjacent to a highway which condensed the area of the site and is also one of the most dangerous work-sites to be on because of all the outside distraction and hazards (Pratt et al. 2001).

Table 4.5: Proximity Device Consistency Measurements

Distance (m)	Avg. Dist. (m)	Std. Dev. (m)
44.588	45.174	1.940
46.751		
45.179		
47.096		
42.255		

#### 4.3.3 Stage 3 – Final Field Trials

The next step is to implement the system into a long-term field trial. The prototype will be integrated into the safety measures on a construction site of a project. A long-term case study will demonstrate the defaults of the prototype in dealing with the rigors of a construction site, the ability for it to stand up to various weather conditions, different tasks such as excavations and multiple story projects, and different obstacles that have the ability to obstruct or diminish the signal will be shown. Then the impact of safety will be measured by calculating the number of “near-misses” that occur through the use of the proximity detection system.

#### **4.4 Evaluation**

Once testing is completed a total evaluation of the technology will be performed. Interviews will be conducted with workers who used the device to discover the uses and limitations that a proximity warning device has to offer. Also, it will aid in determining what workers feel is needed on the construction site in order to improve safety. The interviews will hopefully discover what kind of intervention the workers are willing to have, how much monitoring and watching they do not mind having, and what they think of the proposed technology. The interviews will determine if workers think pro-active-real-time personnel warning system will make a difference, and if they think the PPU is a comfortable, good style of protection device. Also, the impact of the device on safety will be evaluated along with a cost-benefit analysis. Although it is difficult to put a price tag on someone's life, insurance costs, time lost due to accidents, and lawsuits will be taken into consideration against the cost of implementing a proximity-warning device.

## **CHAPTER 5: FURTHER DEVELOPMENT**

This research provides a library of 3D blind spots to aid in the determination of the safety zones for construction equipment. Determination of the necessary safety zones for construction equipment is dependent on many factors such as vehicle speed, percentage of blind spots, the actual task the equipment is performing, and other possible variables. This research concludes only on the calculated blind spots, because the scope of this research does not cover the other variables. In analyzing the dump truck, the required safety zone would be recommended as 10 meters due to the large amount of blind spots to the rear of the vehicle existing for a 1.5 tall person or object. The recommended safety zone for the roller is 8 m; the roller has much better rear-view visibility than the dump truck, even without the mirrors.

Future research should strive to implement object tracking technology, such as ultra-wideband (UWB) technology, to incorporate the proximity alarming and tracking and monitoring technologies into one ergonomic device that construction workers may wear to be protected. Figure 5.1 is a flowchart depicting the internal organization and structure of the stakeholders' real-time pro-active safety management system. This research applies to the safety management portion of the flowchart.

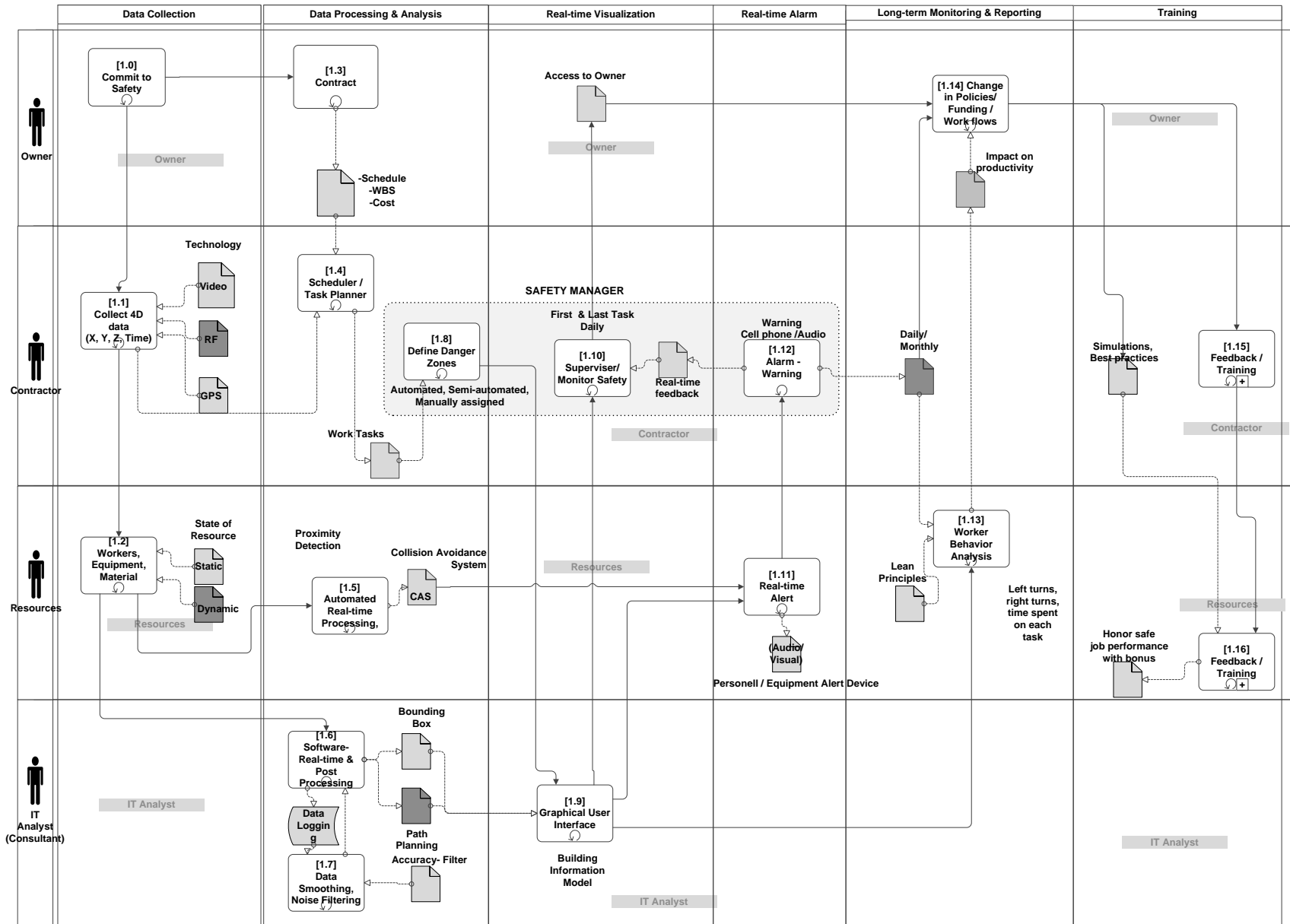


Figure 5.1: Flowchart of Information Flow – Value-added Interactions

## **CHAPTER 6: CONCLUSION**

From the preliminary results and background review the proposed technology has proven to have the possibility of being effective in aiding the safety needs in the construction environment. Current safety practices are not sufficient in preventing worker fatalities on a daily basis when in close proximity to heavy equipment. Furthermore, blind spot measurements show that there is a need in giving aide to equipment operators because of their limited FOV. The analysis of the blind spots provided a basis on which to determine necessary safety zones for construction equipment. The developed proximity device can detect the presence of heavy equipment, including a forklift, excavator, dozer, and dump truck. Based on signal strength, the device can simultaneously activate and warn workers and equipment operators from being too close to each other – capability of the device is sufficient to satisfy the developed safety zones for construction equipment.

When working in a construction environment, the PPU and EPU were both effective at alerting personnel of the danger through auditory, visual, and vibrating alarms even when surrounded by noise and distractions. The technology has the capability to implement a recording device to collect the currently unrecorded data of close calls and near misses. This data will be analyzed and used in future research to improve positioning of workers and equipment and assist in the development of new safety concepts and training.

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## **APPENDIX A: EXPERIMENT 1 FIGURES**

Appendix A figures show the blind spots for the equipment analyzed. The radius throughout all of Appendix A is 10 meters radius. Each equipment has four corresponding figures; the first is the operator's "eye" level or default position of the laser scanner during data collection, the second and third show the blind spots for a 1.8 m and 1.5 meter tall person, and the fourth and final figure for each equipment shows the blind spots on the ground level. Figures A.1-4 corresponds to the bulldozer. Figures A.5-8 corresponds to the pick-up truck. Figures A.9-12 corresponds to the dump truck. Figures A.13-16 corresponds to the roller. Figures A.17-20 corresponds to the excavator. Figures A.21-24 corresponds to the motor grader.

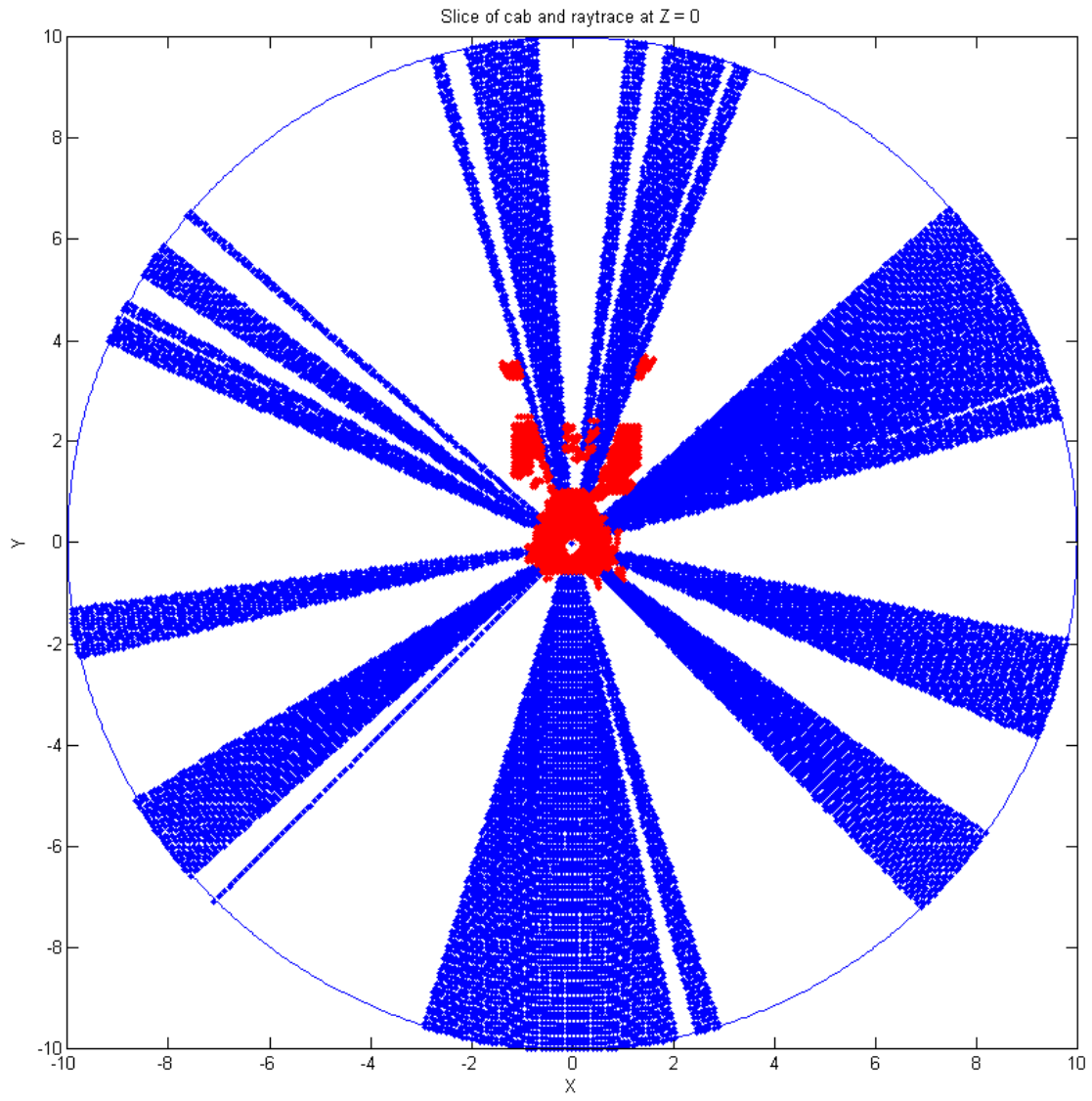


Figure A.1: Bulldozer blind spots eye level ( $z = 0$  m);  $r = 10$ m.

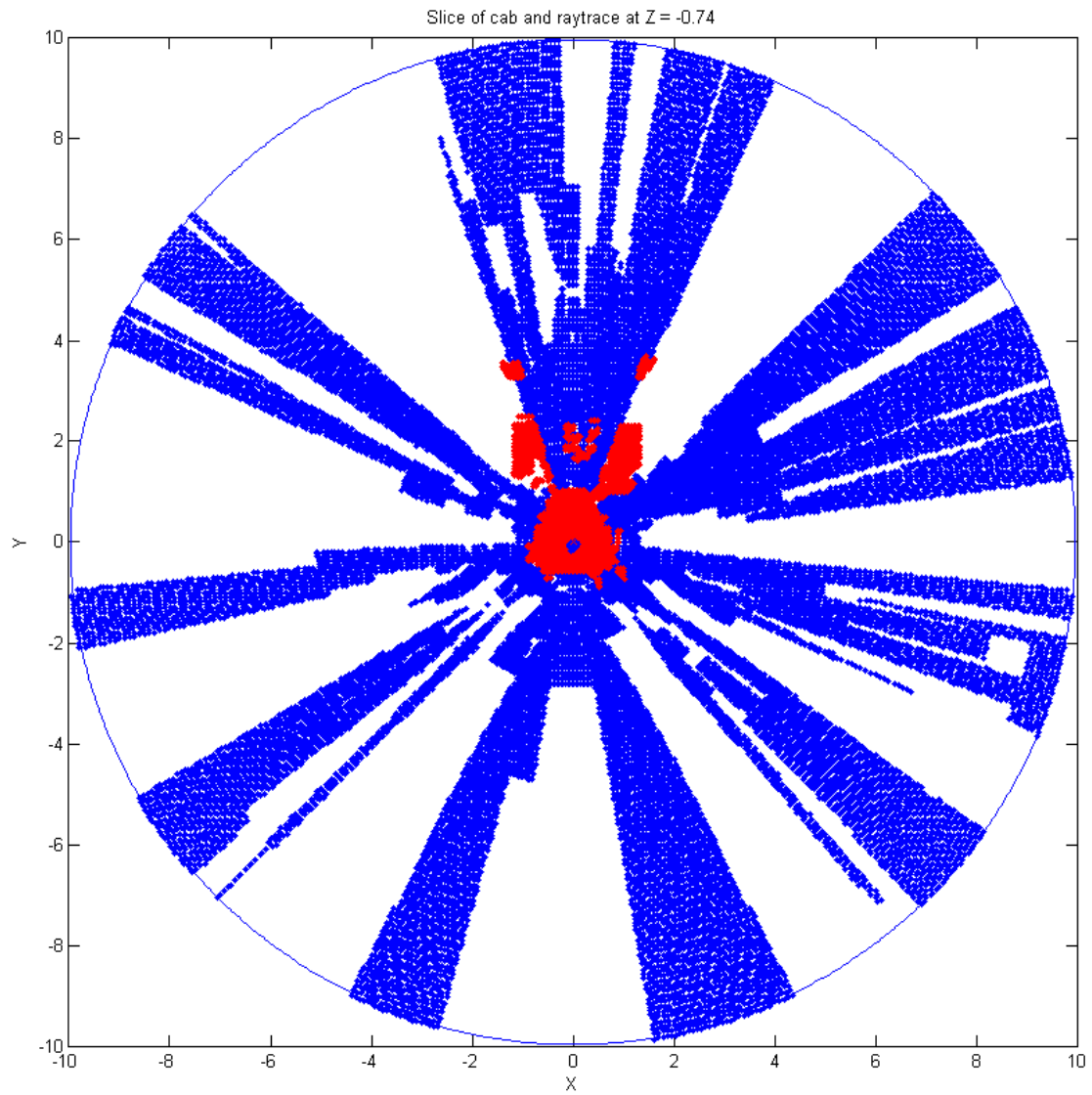


Figure A.2: Bullozer blind spots 1.8 m tall person ( $z = -0.74$  m);  $r = 10$  m.

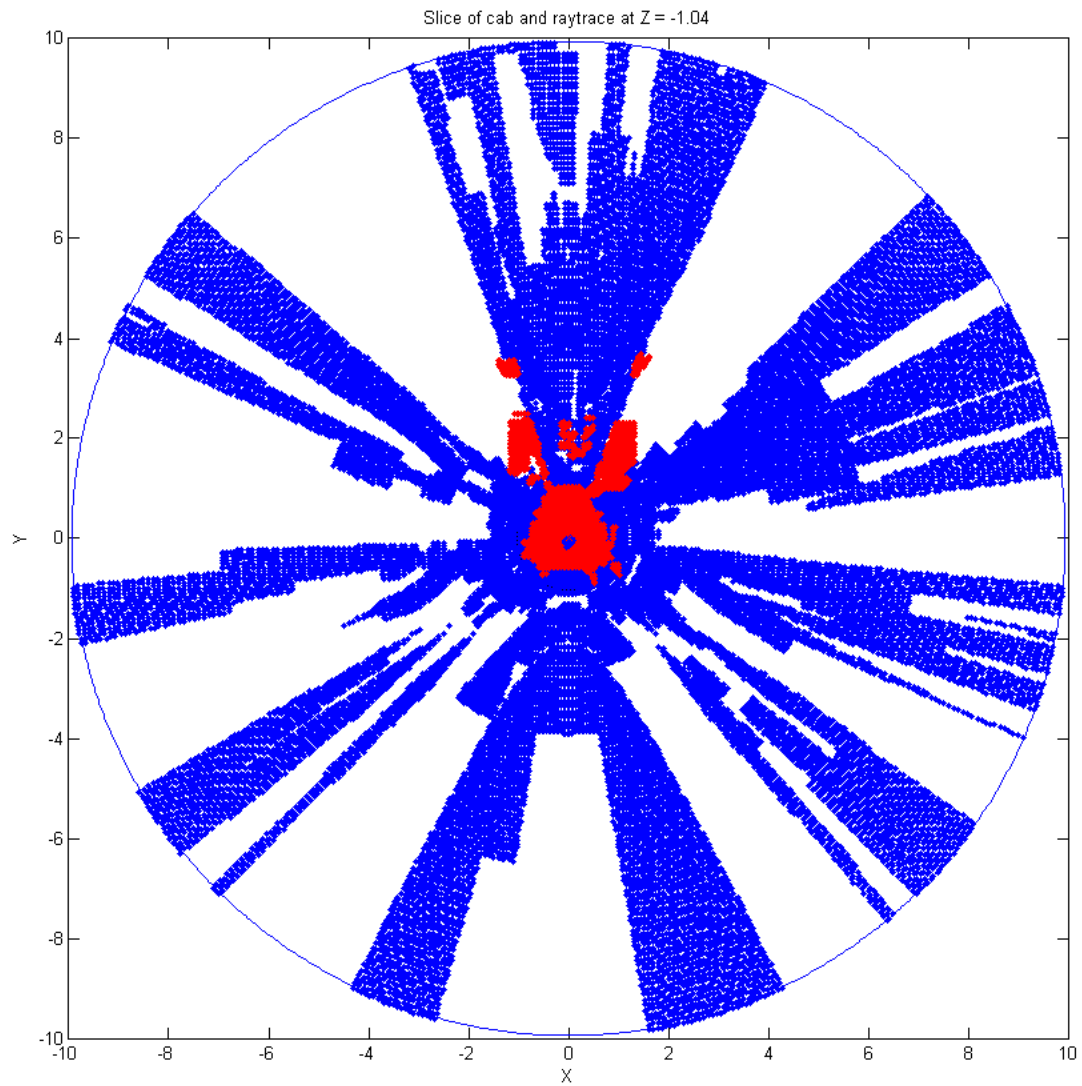


Figure A.3: Bulldozer blind spots 1.5 m tall person ( $z = -1.04$  m);  $r = 10$  m.

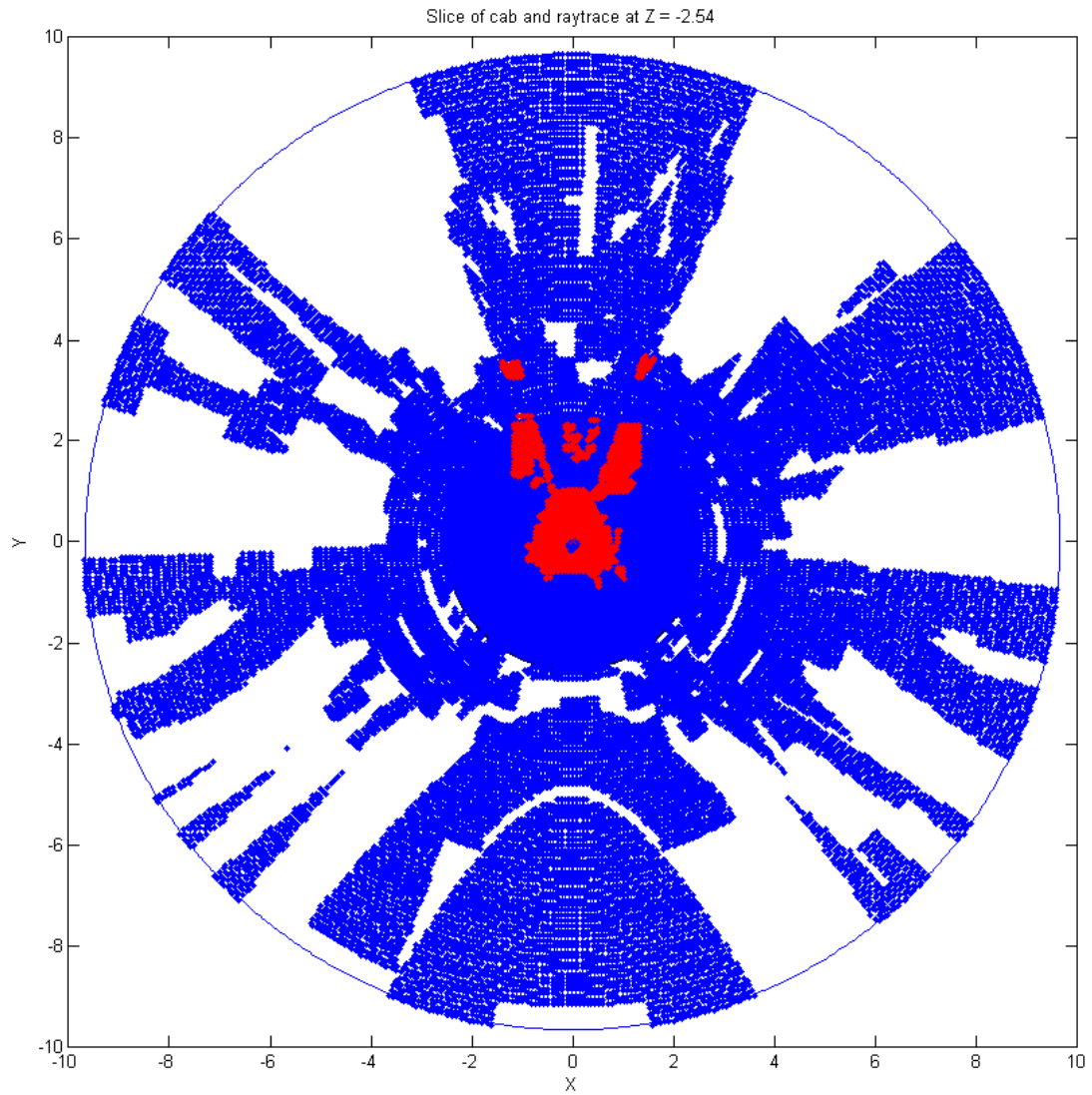


Figure A. 4: Bulldozer blind spots ground level ( $z = -2.54$  m);  $r = 10$ m.

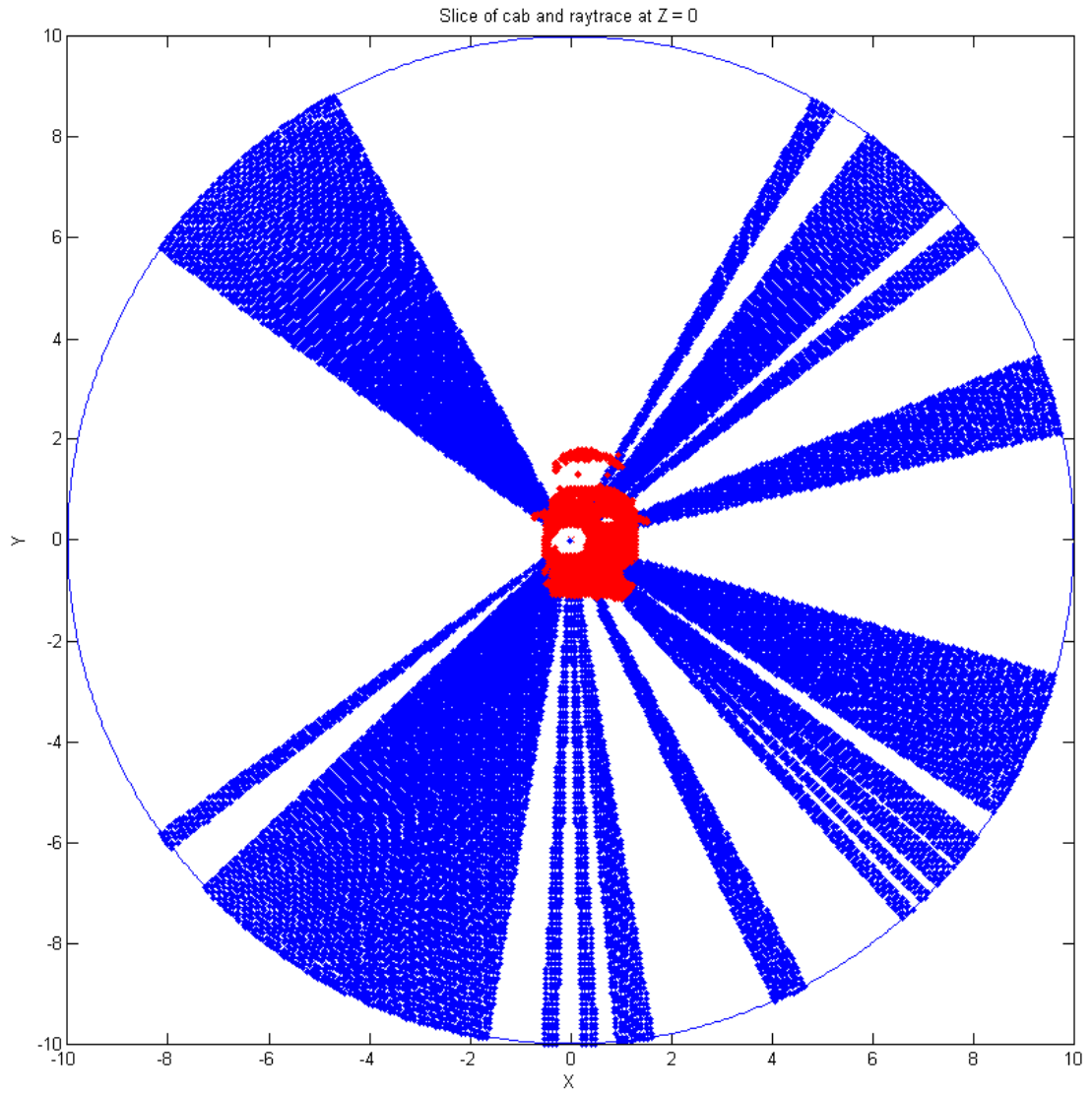


Figure A.5: Pick-up Truck blind spots eye level ( $z = 0$  m);  $r = 10$  m.

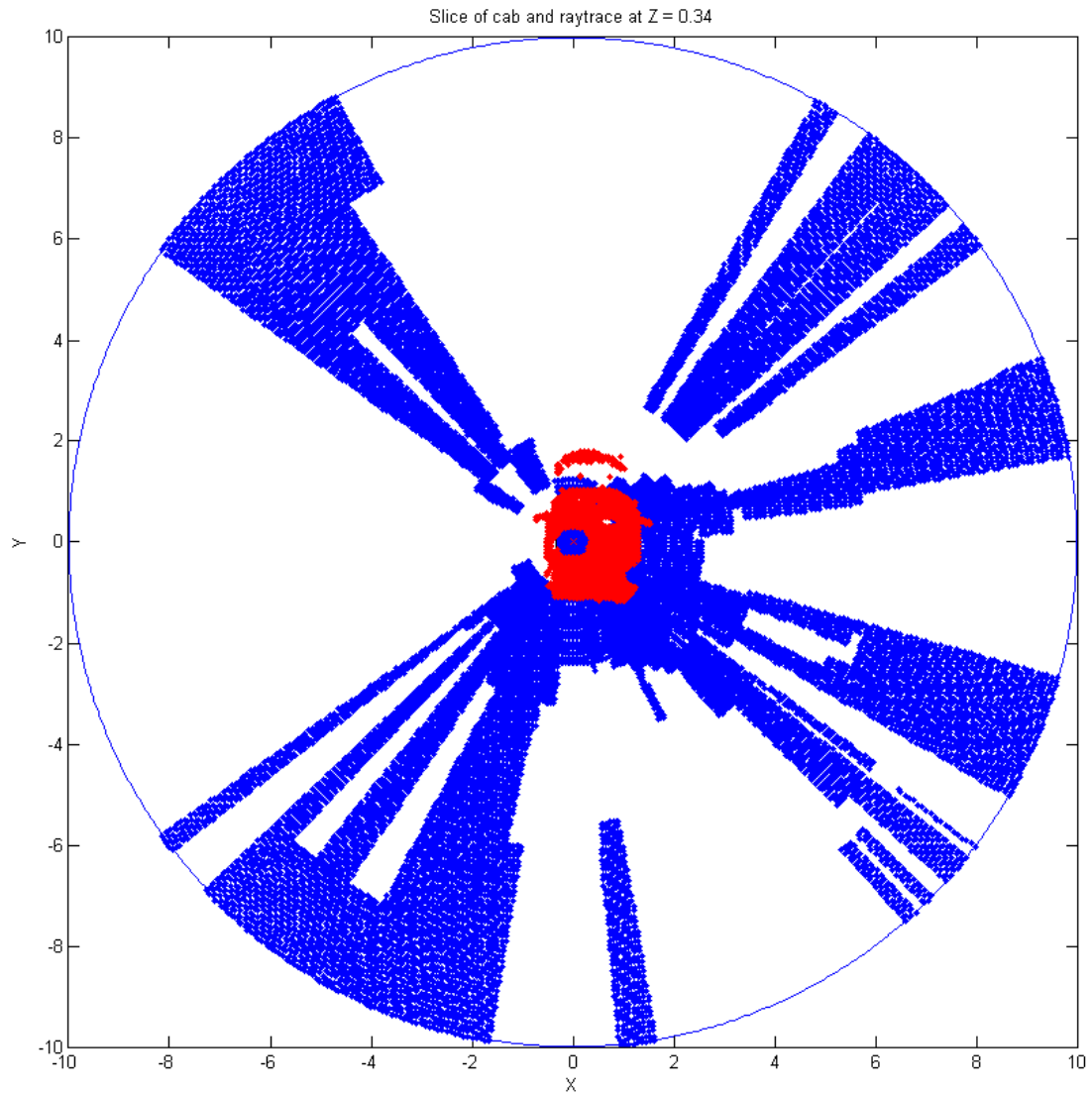


Figure A.6: Pick-up Truck blind spots 1.8 m tall person ( $z = 0.34$  m);  $r = 10$ m.



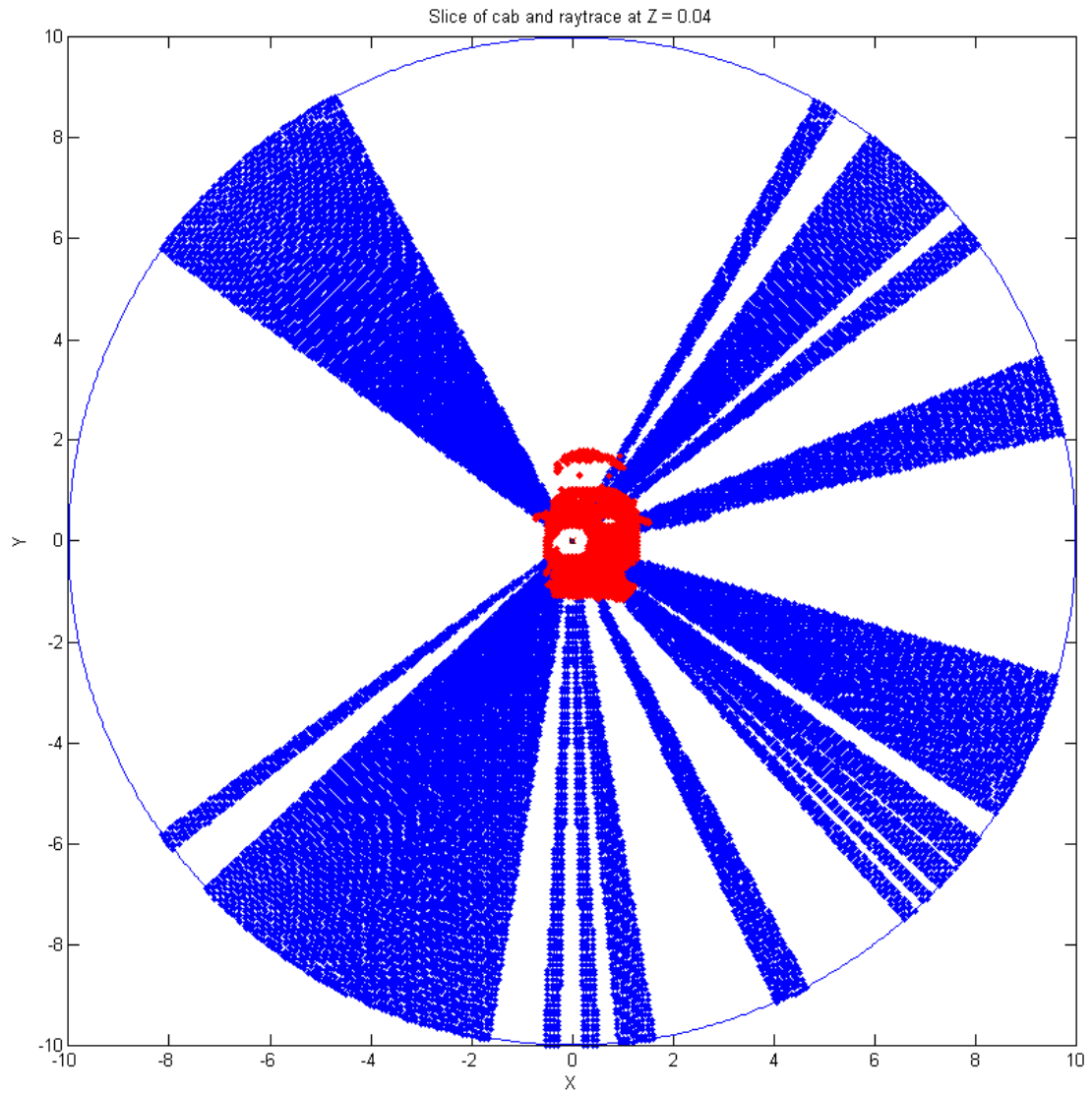


Figure A.7: Pick-up Truck blind spots 1.5 m tall person ( $z = 0.04$  m);  $r = 10$ m.

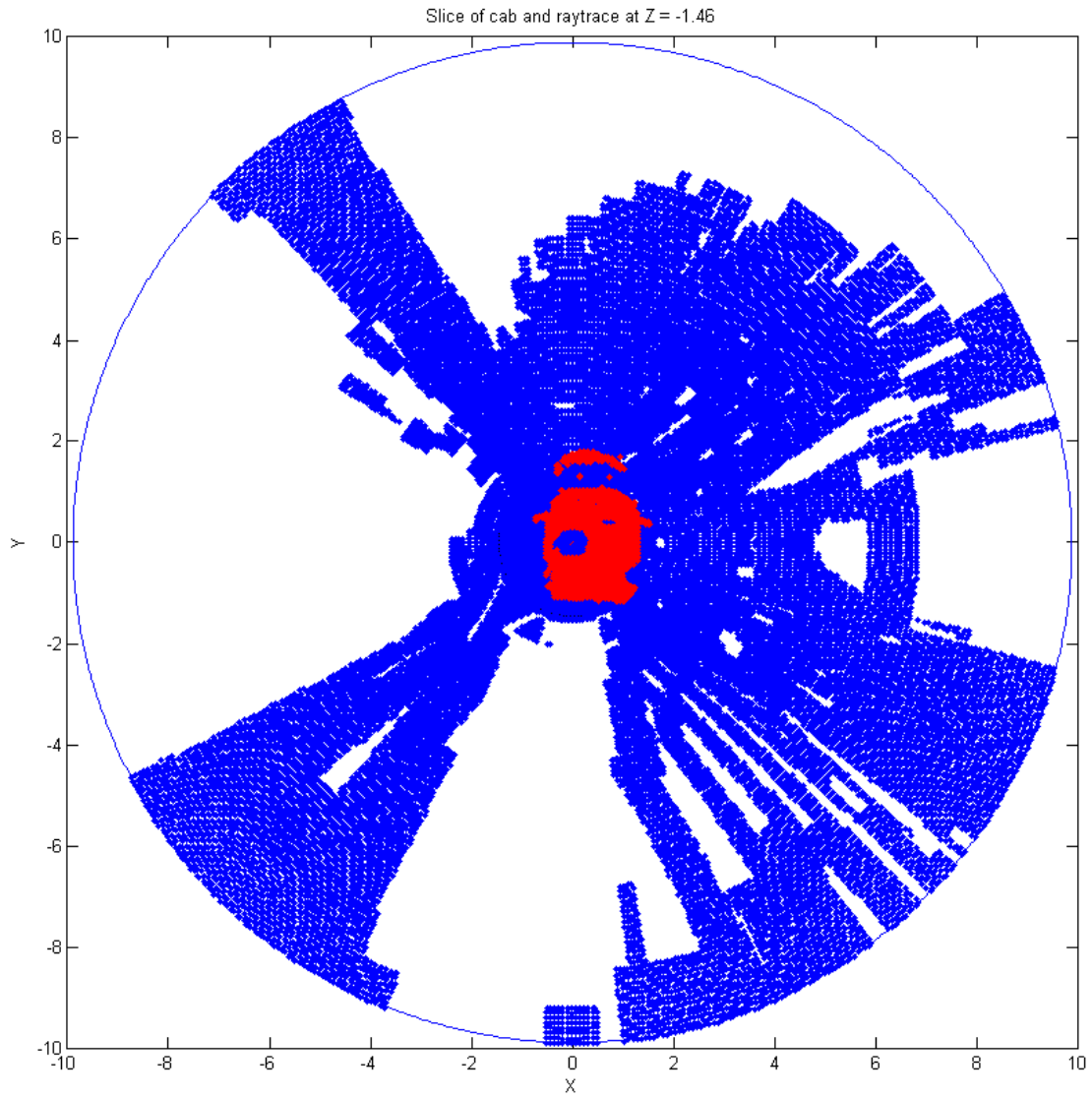


Figure A.8: Pick-up Truck blind spots ground level ( $z = -1.46$  m);  $r = 10$  m.

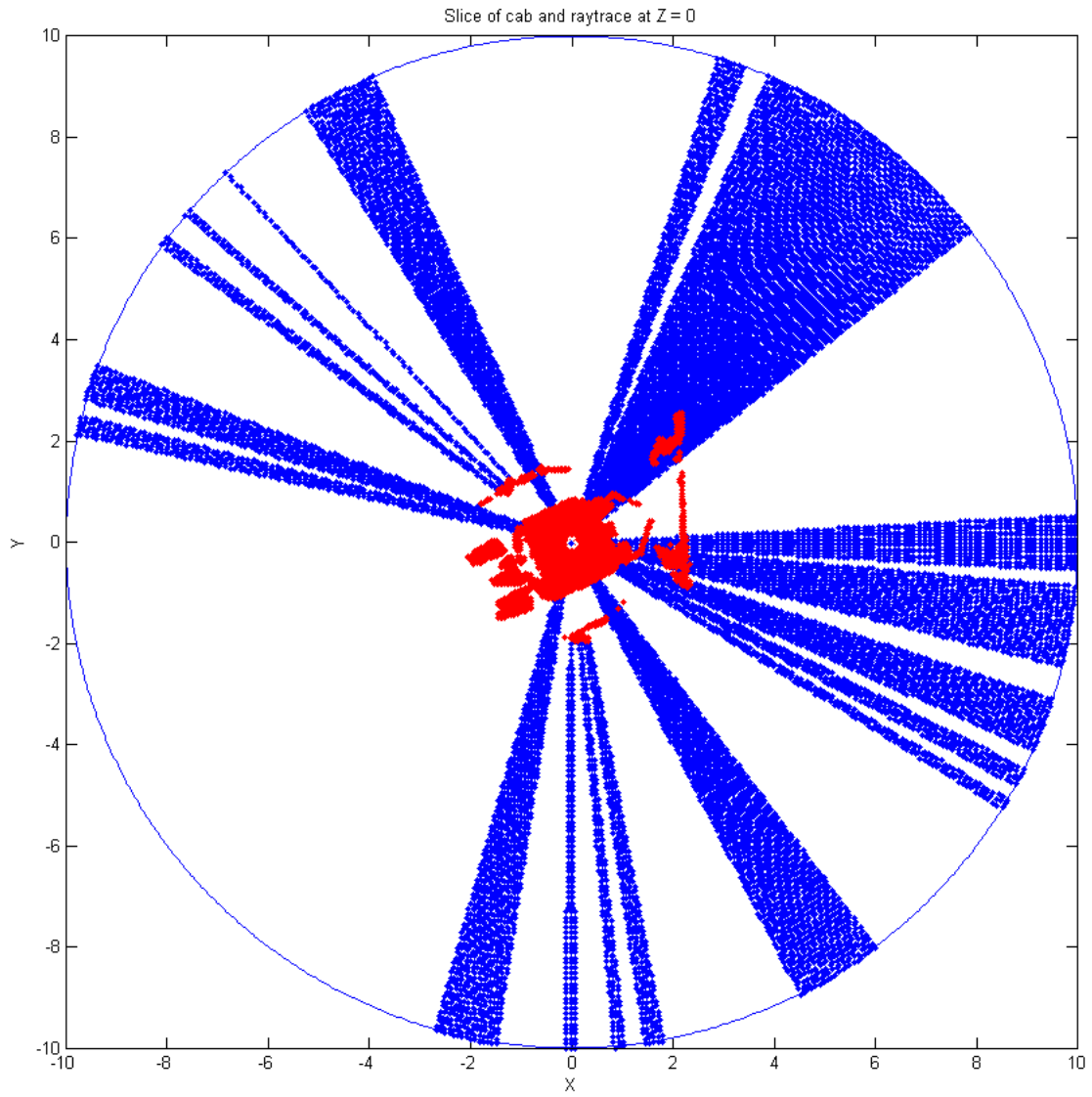


Figure A.9: Dump Truck blind spots eye level ( $z = 0$  m);  $r = 10$  m.

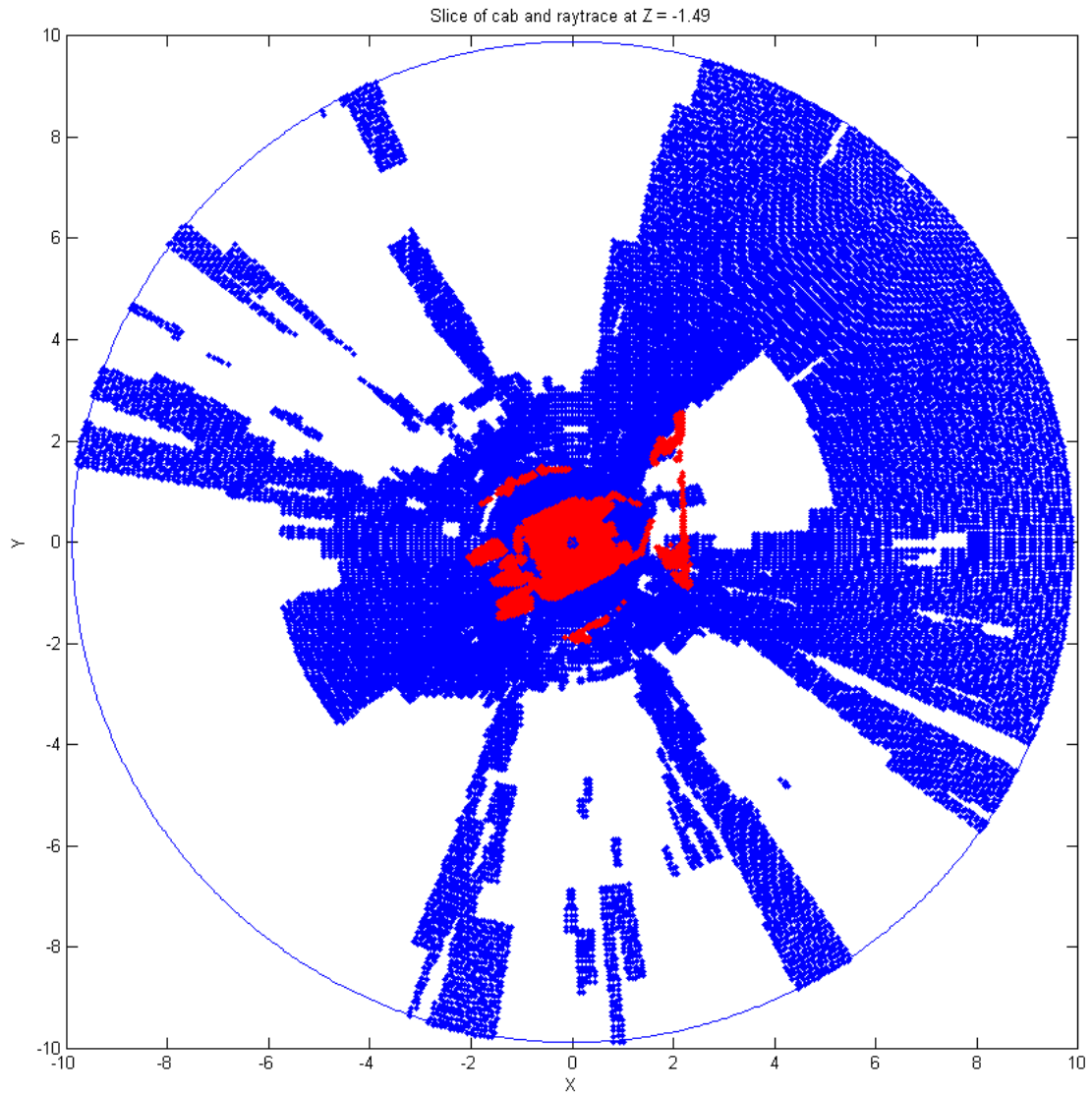


Figure A.10: Dump Truck blind spots 1.8 m tall person ( $z = -1.49$  m);  $r = 10$ m.

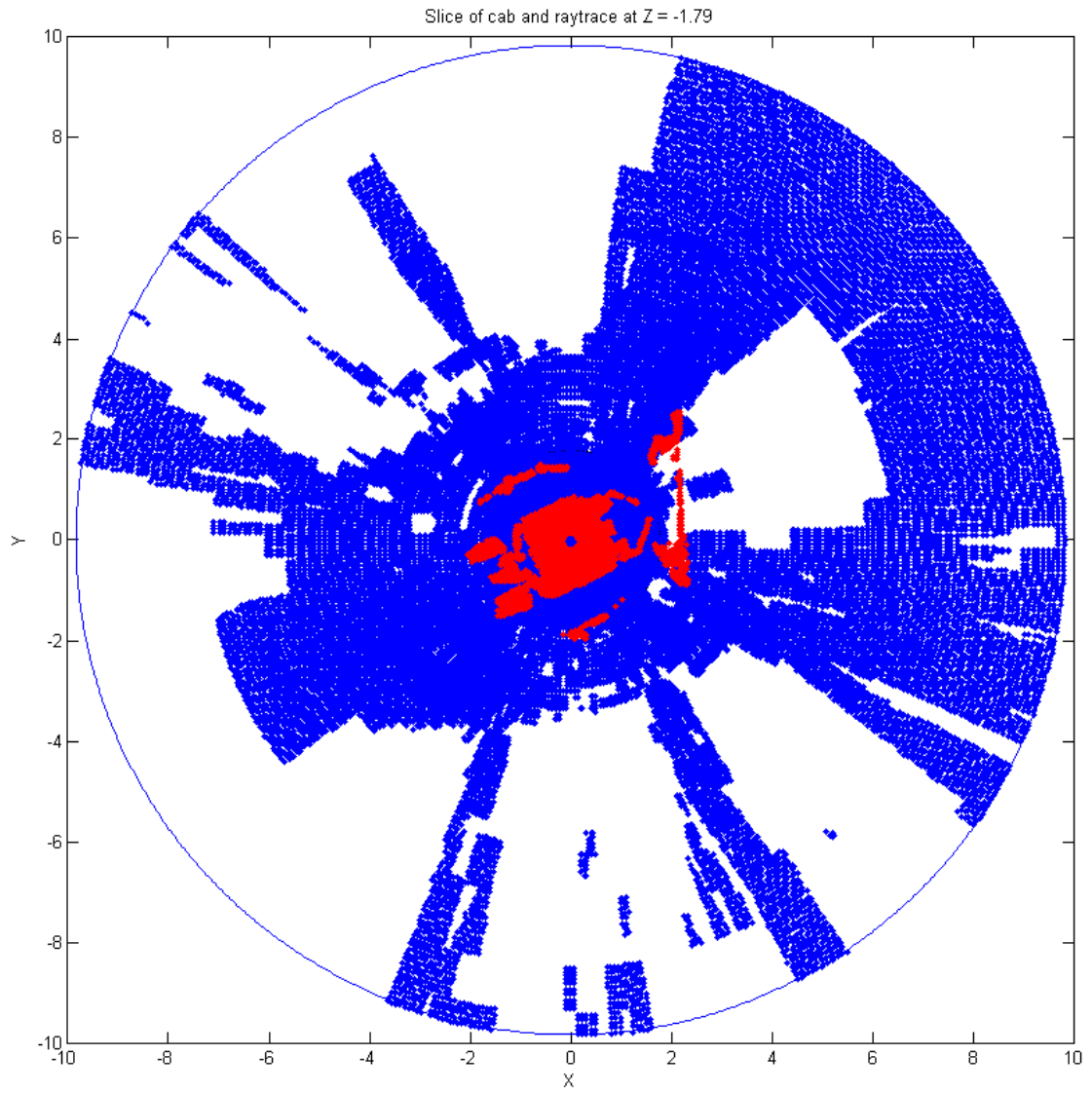


Figure A.11: Dump Truck blind spots 1.5 m tall person ( $z = -1.79$  m);  $r = 10$ m.

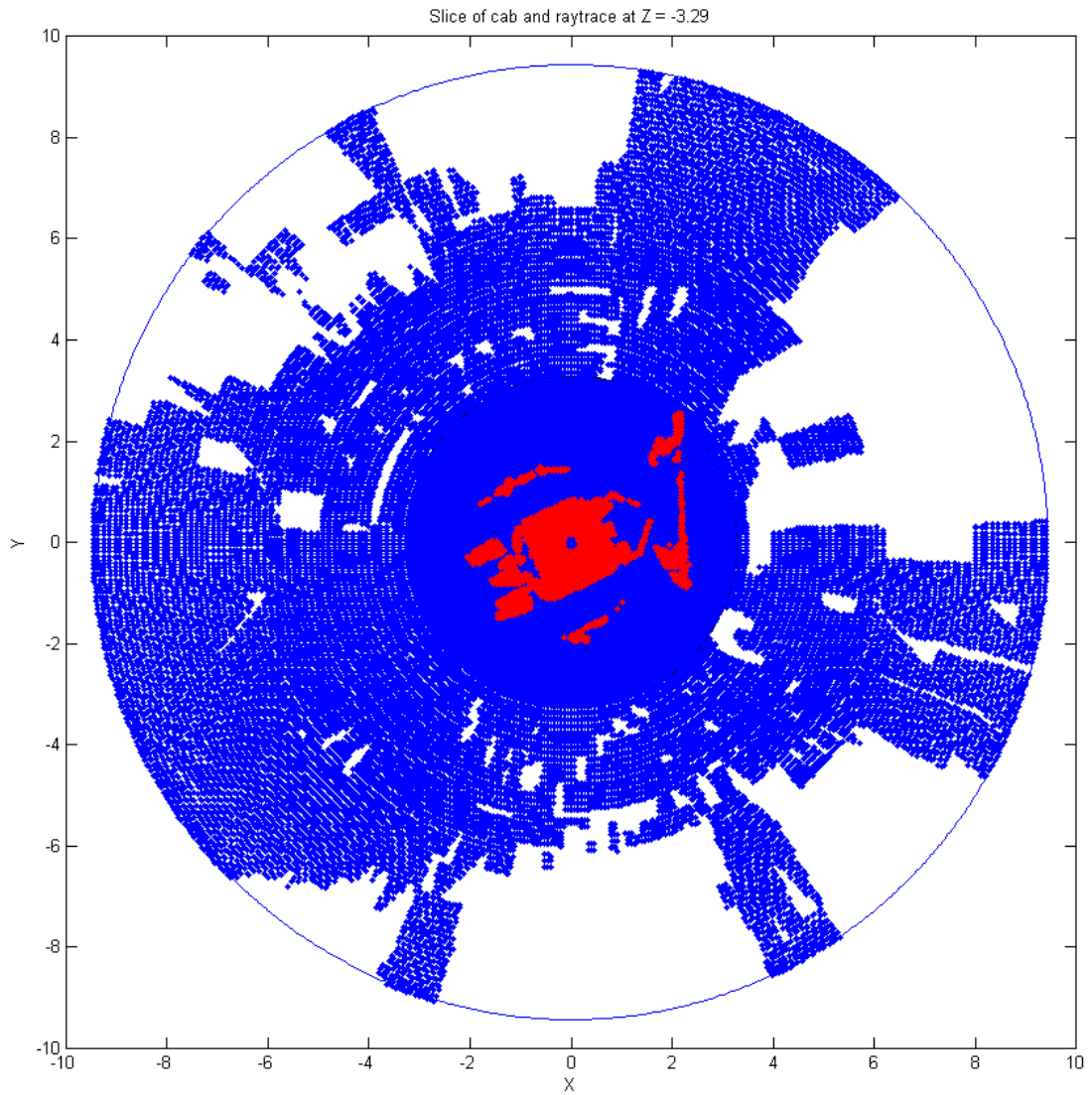


Figure A.12: Dump Truck blind spots ground level ( $z = -3.29$  m);  $r = 10$  m.

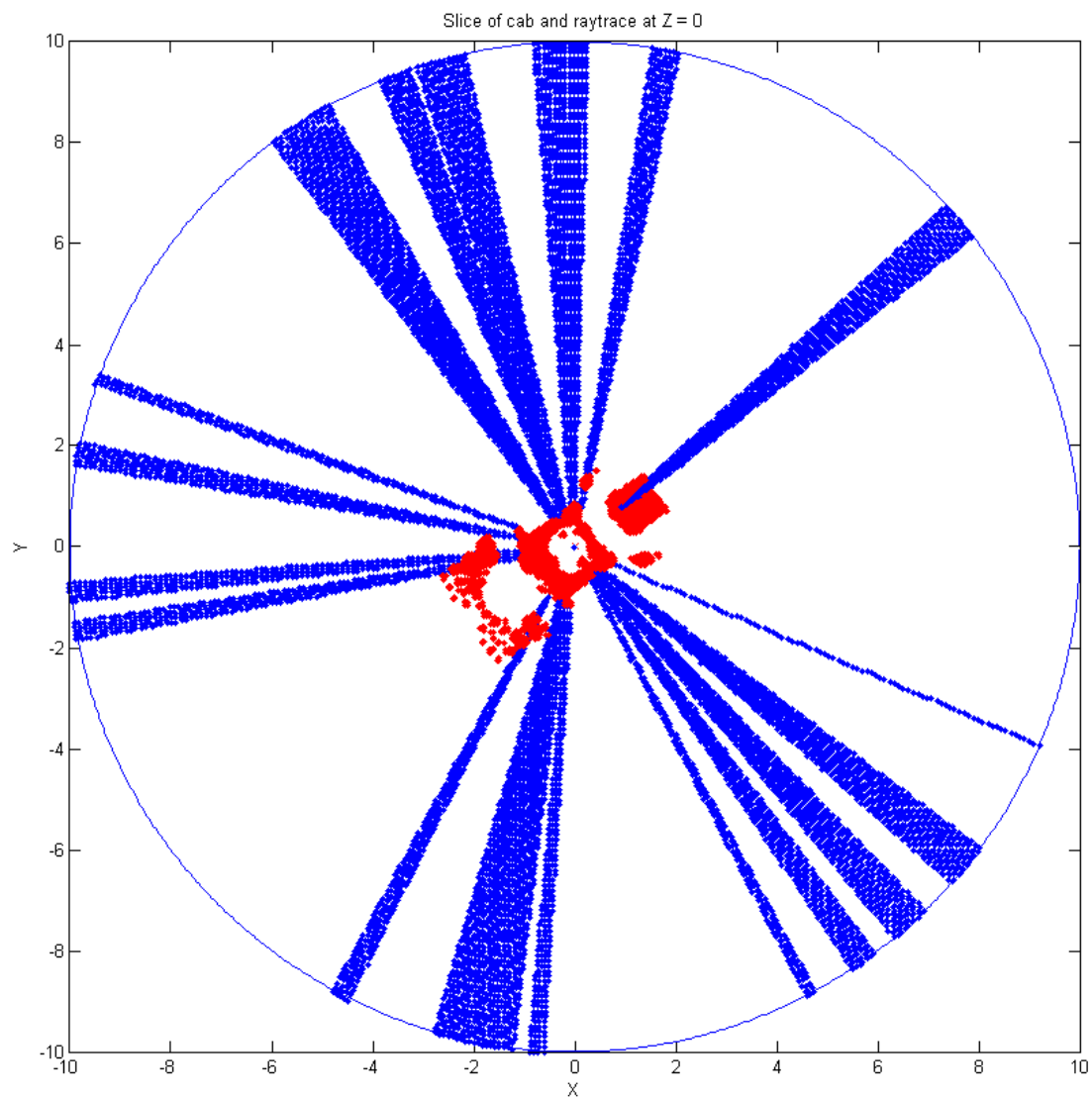


Figure A.13: Roller blind spots eye level ( $z = 0$  m);  $r = 10$ m.

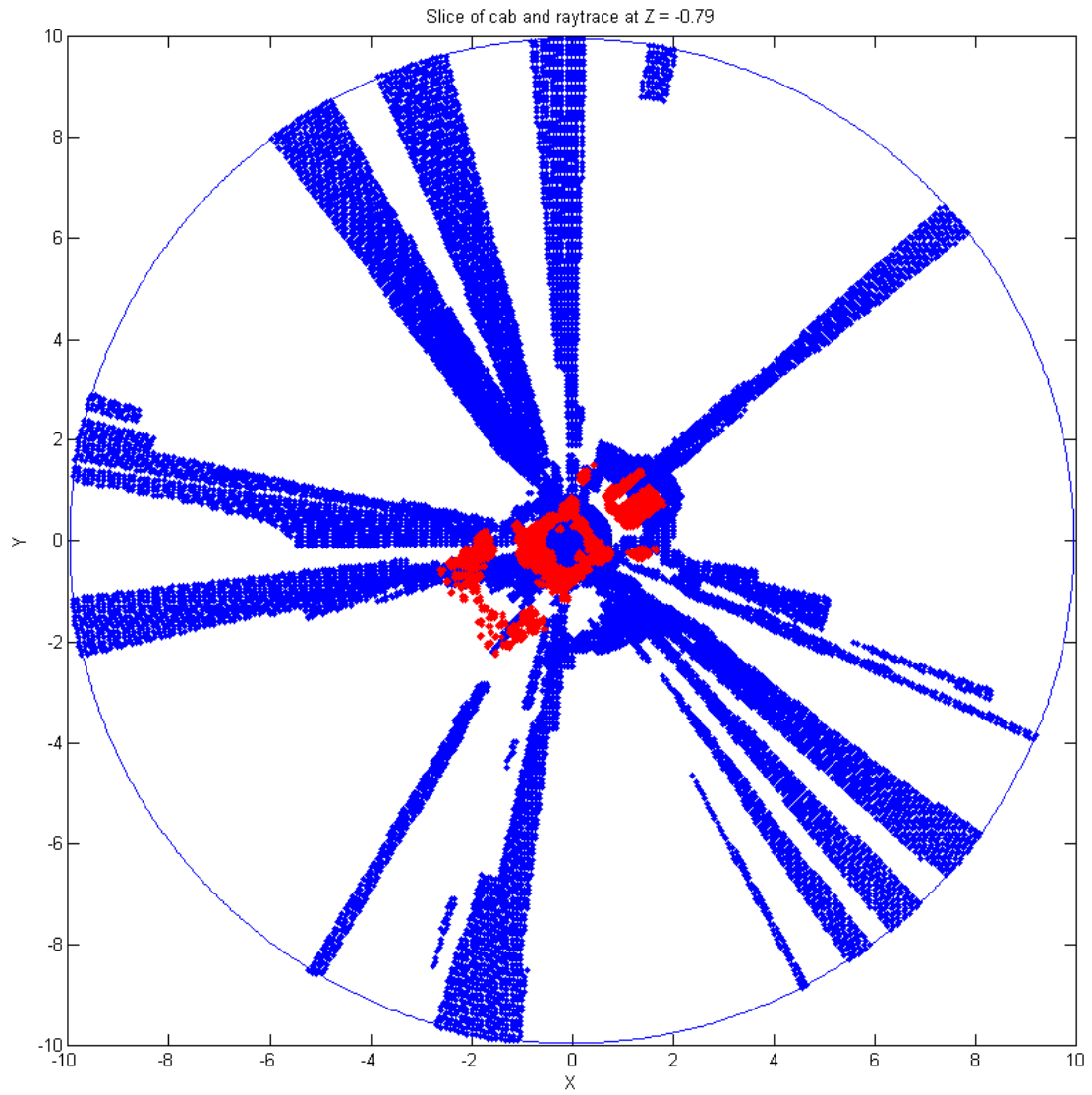


Figure A.14: Roller blind spots 1.8 m tall person ( $z = -0.79$  m);  $r = 10$  m.



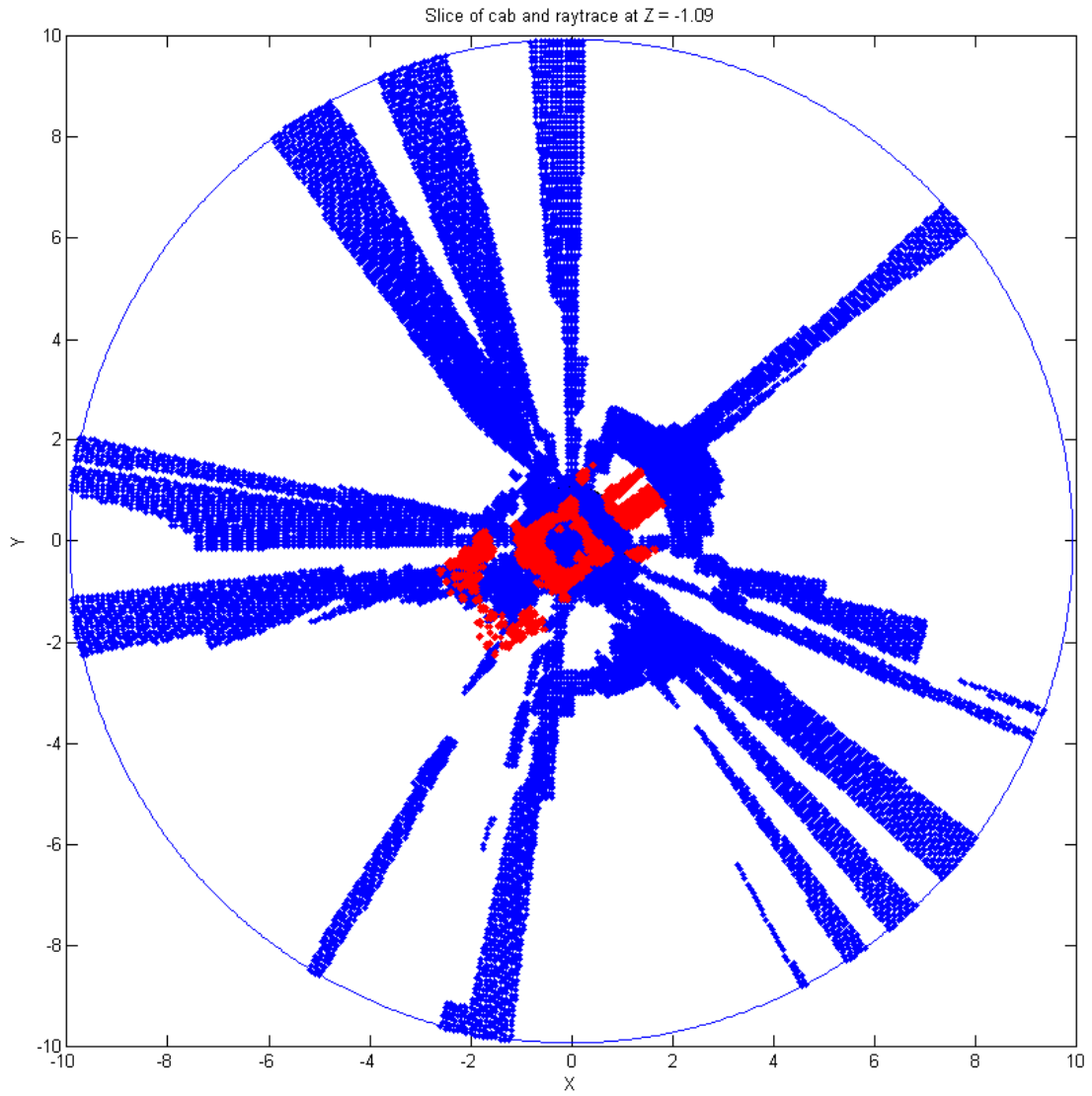


Figure A.15: Roller blind spots 1.5 m tall person ( $z = -1.09$  m);  $r = 10$  m.

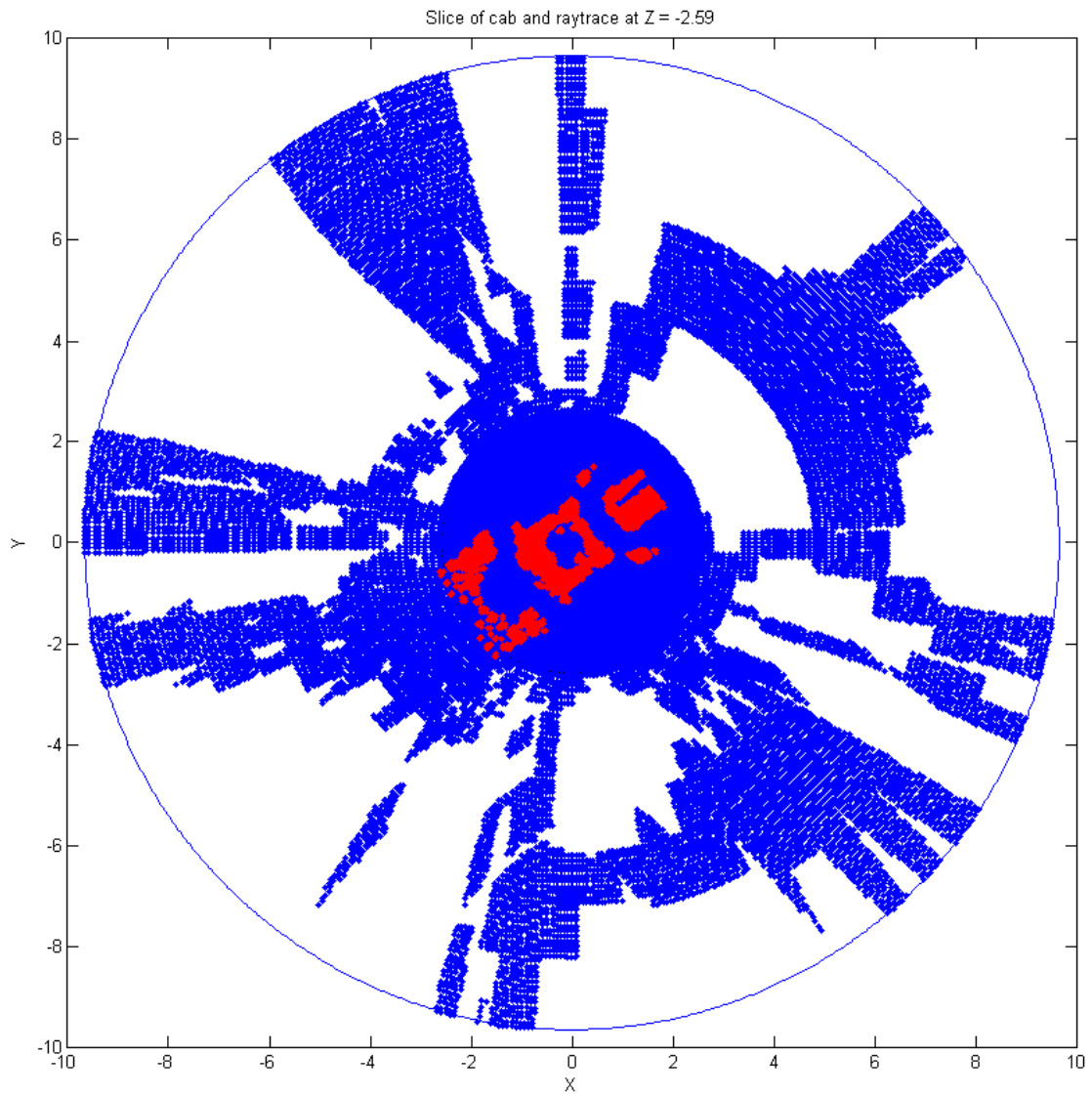


Figure A.16: Roller blind spots ground level ( $z = -2.59$  m);  $r = 10$ m.

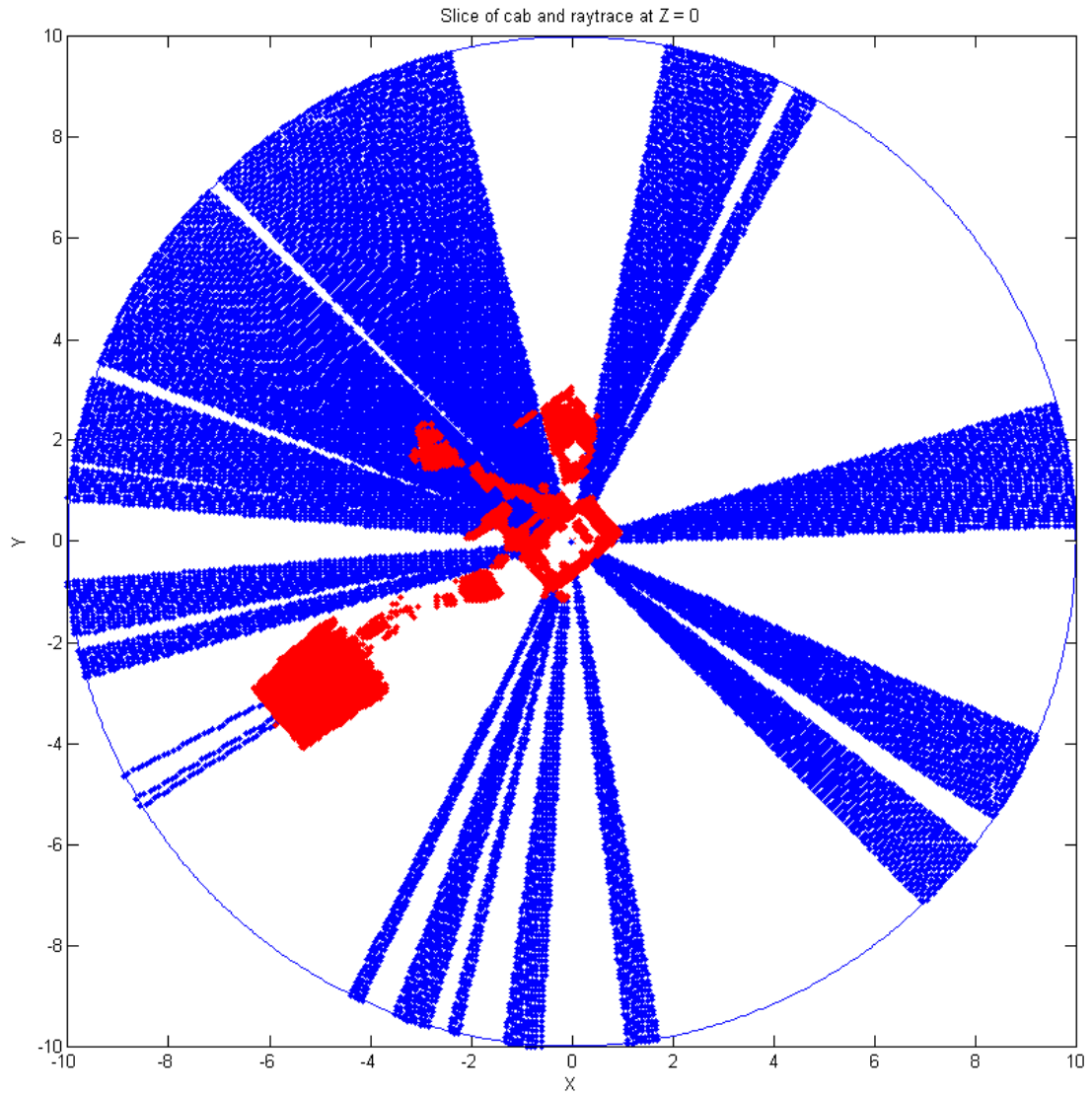


Figure A.17: Excavator blind spots eye level ( $z = 0$  m);  $r = 10$  m.

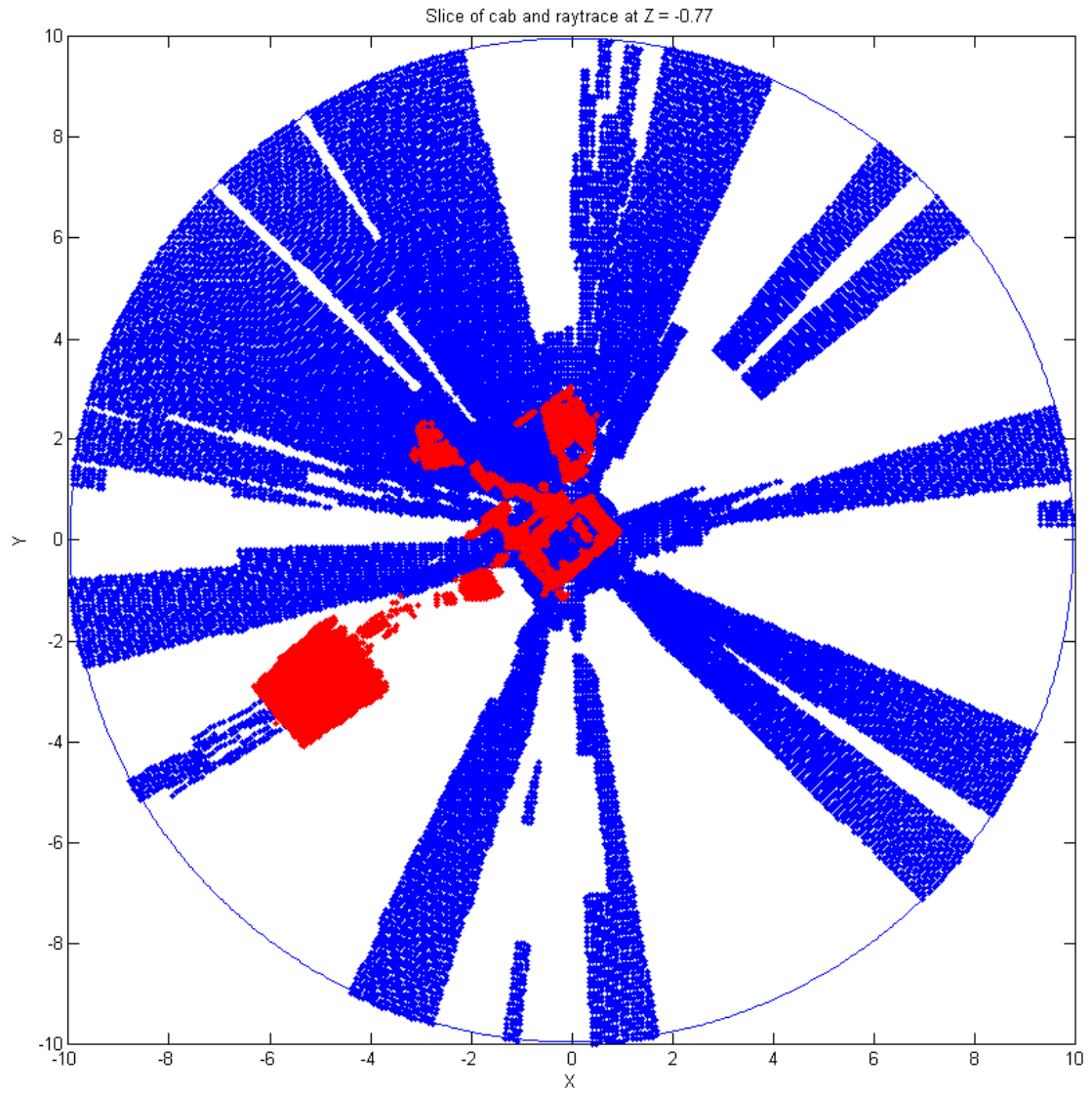


Figure A.18: Excavator blind spots 1.8 m tall person ( $z = -0.77$  m);  $r = 10$  m.

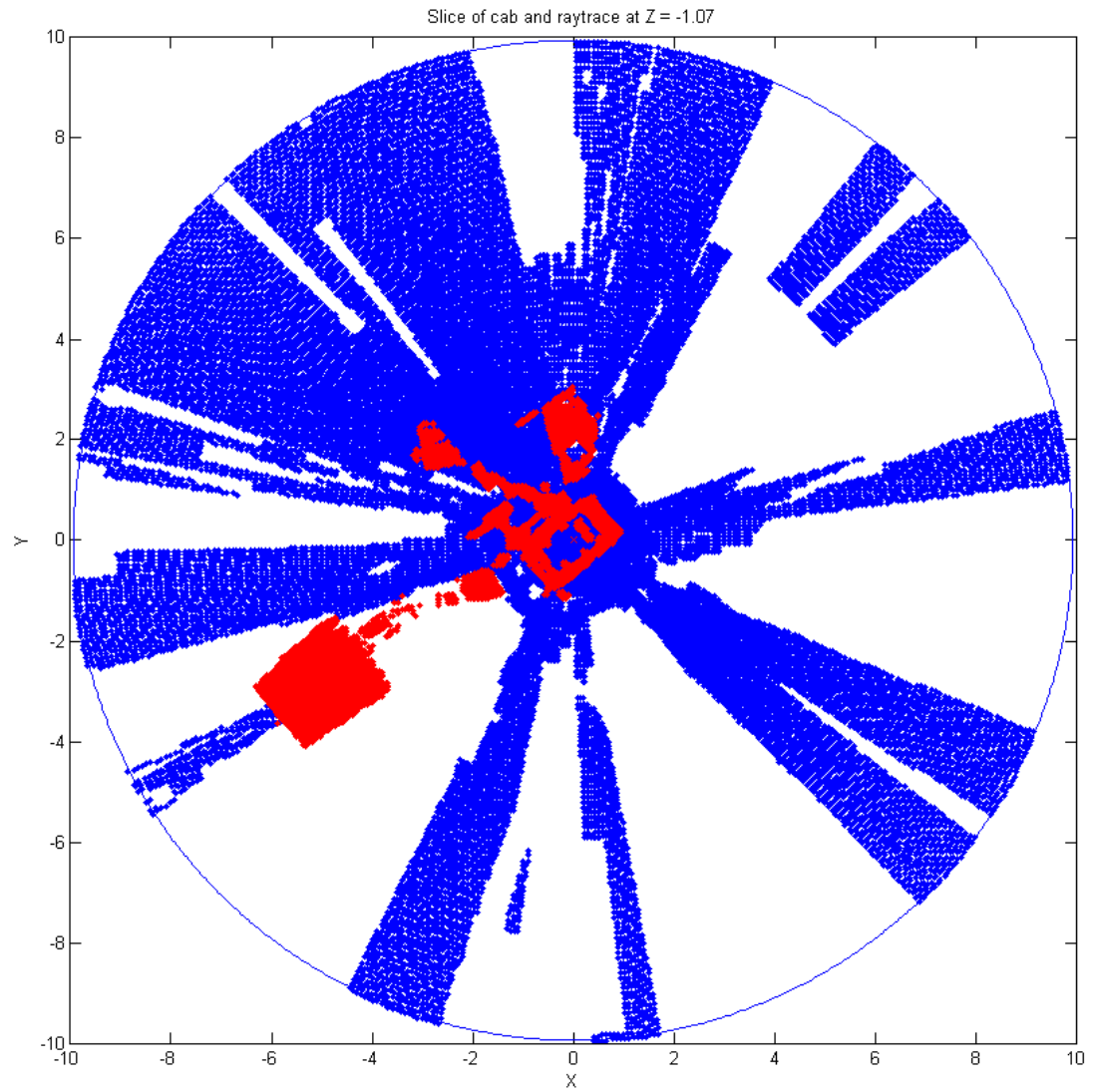


Figure A.19: Excavator blind spots 1.5 m tall person ( $z = -1.07$  m);  $r = 10$  m.

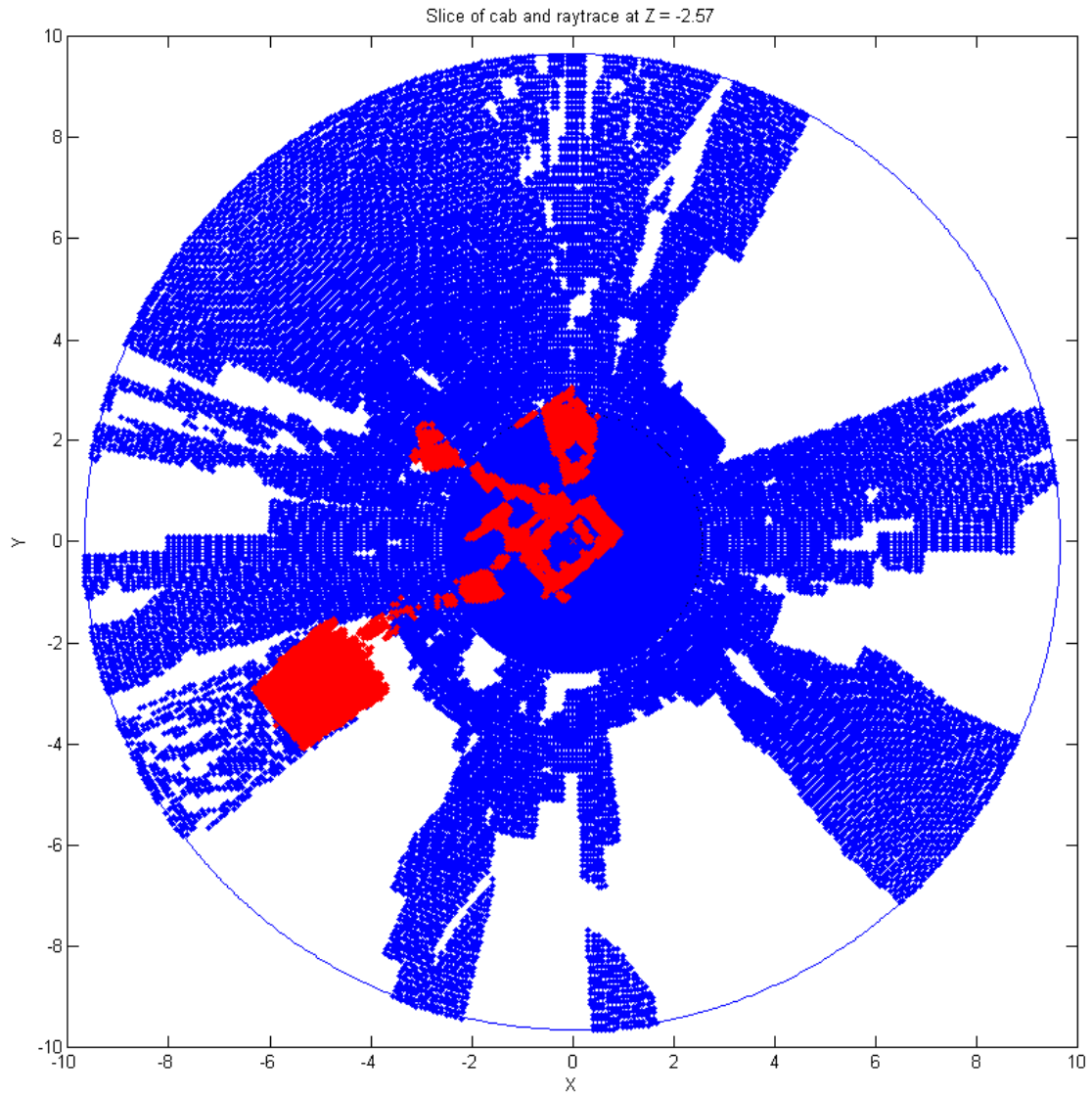


Figure A.20: Excavator blind spots ground level ( $z = -2.57$  m);  $r = 10$  m.

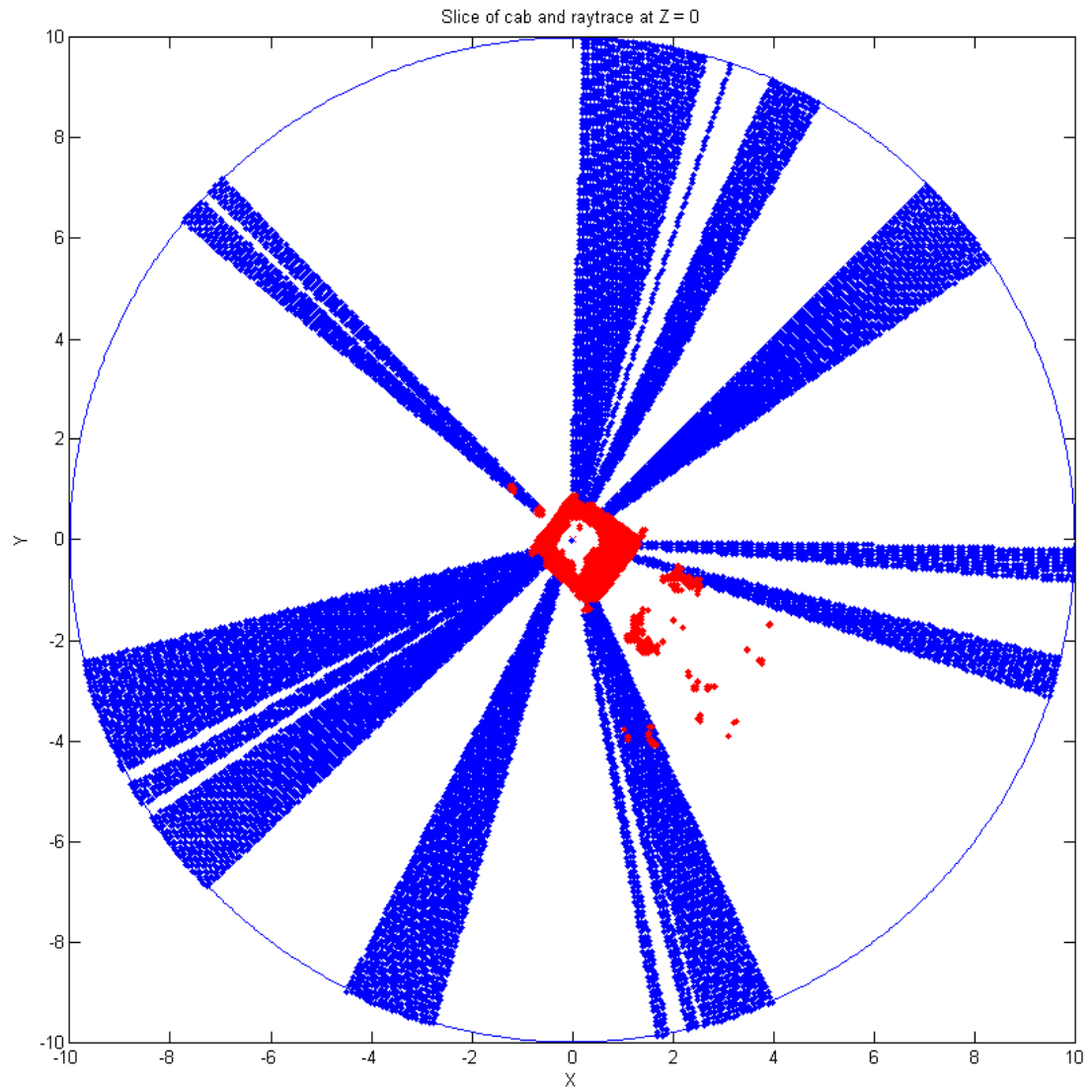


Figure A.21: Motor Grader blind spots eye level ( $z = 0$  m);  $r = 10$  m.

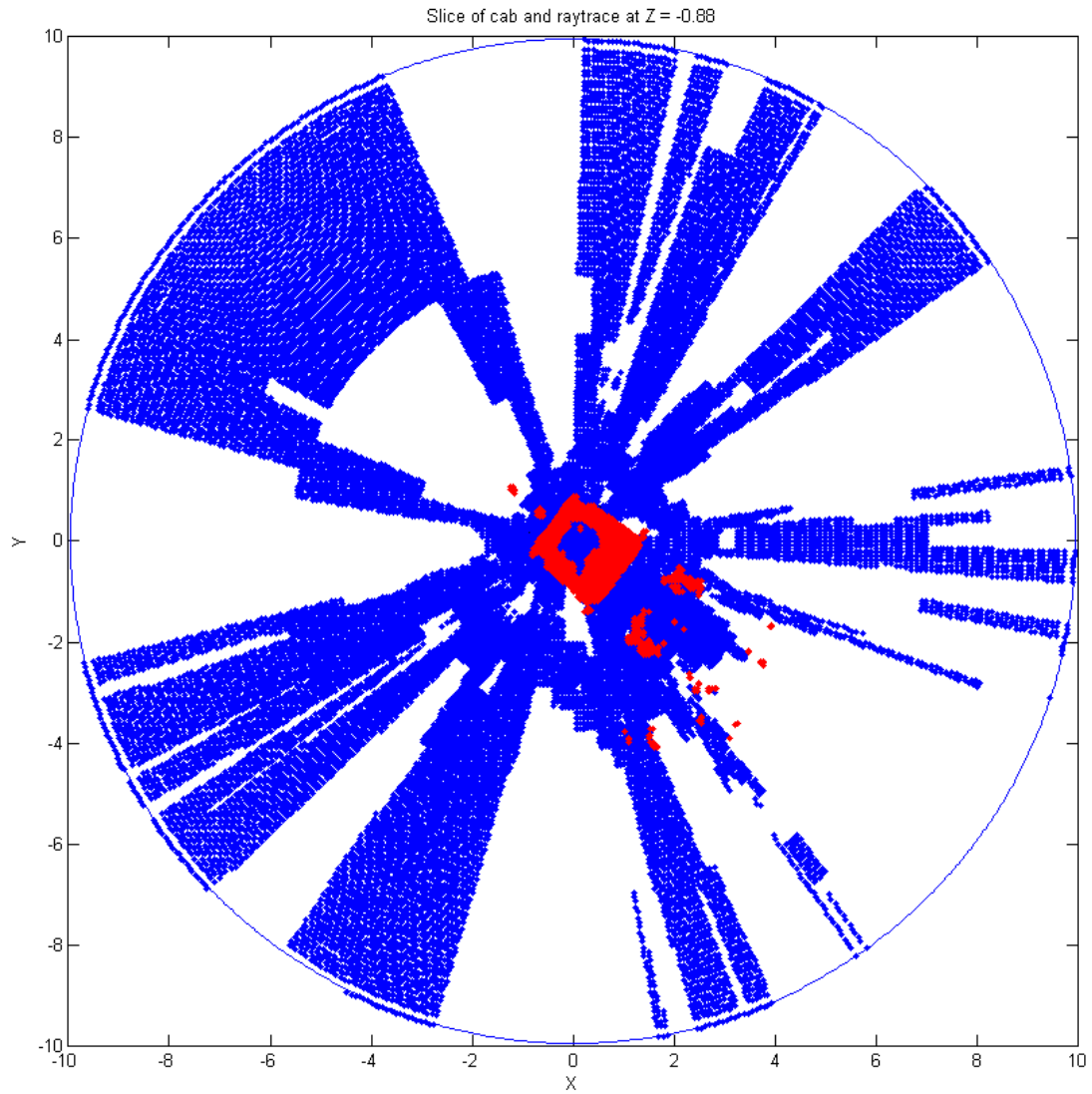


Figure A.22: Motor Grader blind spots 1.8 m tall person ( $z = -0.88$  m);  $r = 10$ m.



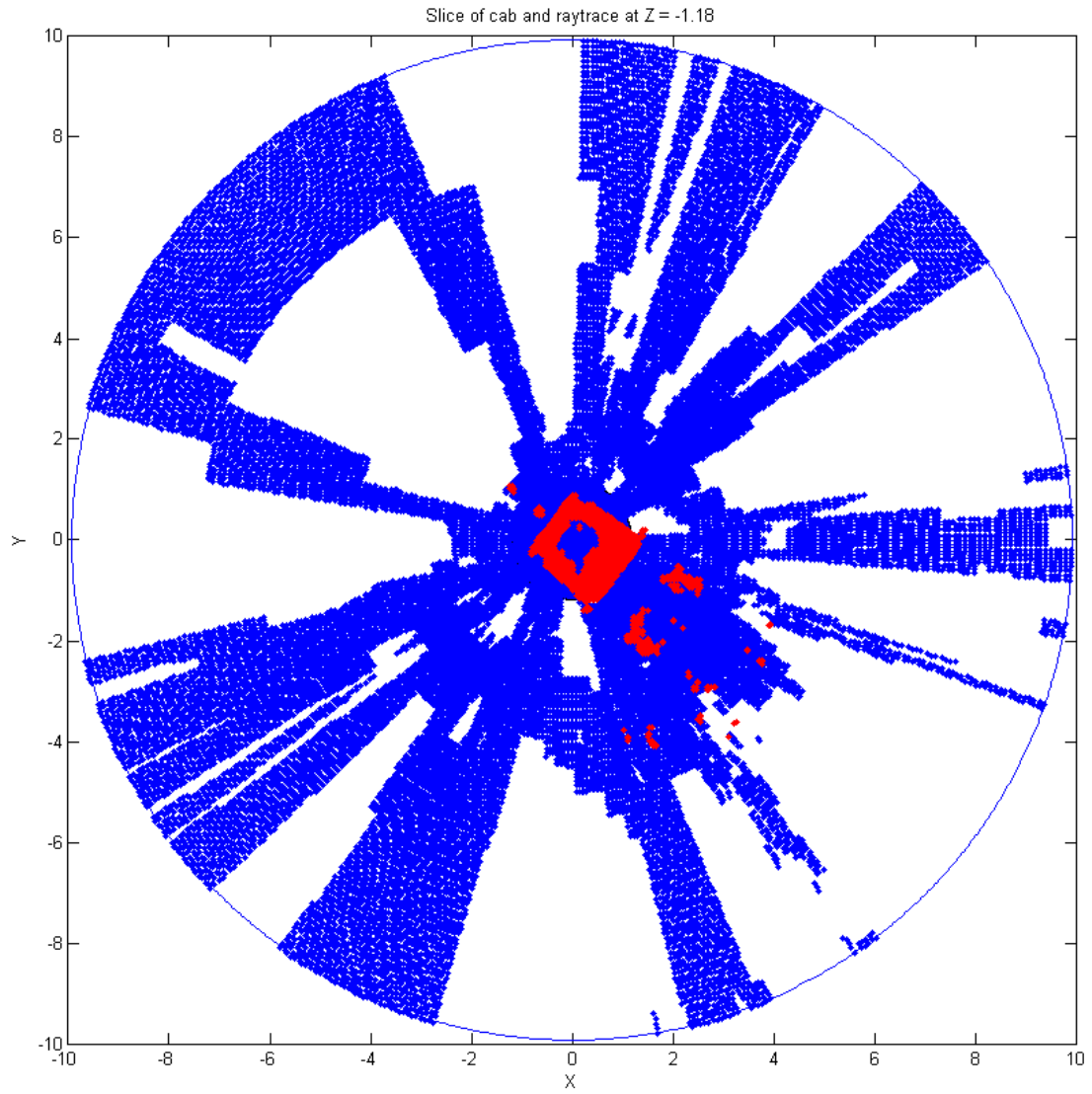


Figure A.23: Motor Grader blind spots 1.5 m tall person ( $z = -1.18$  m);  $r = 10$  m.

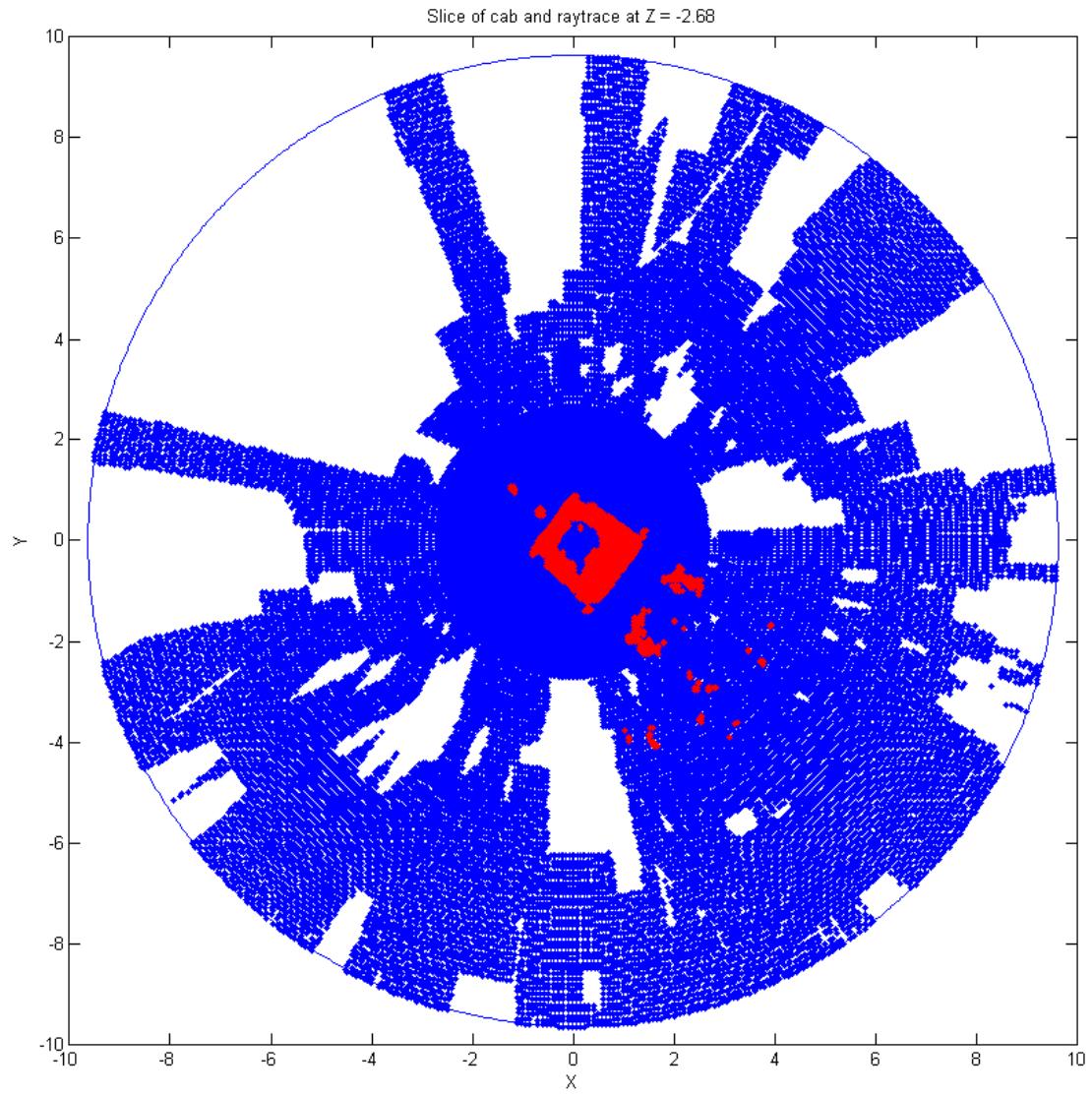


Figure A.24: Motor Grader blind spots ground level ( $z = -2.68$  m);  $r = 10$ m.

## **APPENDIX B: 3D BLIND SPOTS VOLUME CALCULATION**

The developed computer tool can calculate the 3D blind spot percentage for any CSV file. In order to determine the optimum threshold distance to determine the 3D blind spots volume, the distance of 10 meters was chosen to set the cube size of the blocks in the computer tool for this experiment. The default (absolute) maximum number of cubes is 300x300x300. Maximum cubes are used for 10 meters. The number of cubes is adjusted for each distance analyzed. Table B.1 shows the adjusted cube values in chart format, and the percentage of blind spots calculated (corresponds to Figure B.1). All equipment analyzed will have a unique threshold distance because the CSV files differ. Figure B.1 show the curve as analyzed for the dump truck. The threshold distance for the dump truck is approximately 3 m (solid, black, vertical line), resulting in 81.439% 3D blind spots volume. Although the cube sizes were exactly the same the results had a drop in the 3D blind spot percentage between 2.5–3 meters and between 3–3.5 meters. These two “reduced” calculations may be attributed to using nine significant figures in defining the “perfect” sphere radius to obtain an exact integer number of cubes – for example, 1.2 cubes is incalculable in the computer tool – and the reduced numeric results are not statistically significant to affect the data trend. Furthermore, the two data points corresponding to 0.5 m and 1 m radii are merely a matter of “formality”, because in the dump truck CSV file the necessary sphere radius to encapsulate the whole cab is 1.234 m (dashed vertical line), measured in the laser scanning software. The necessary sphere radius to encapsulate the dump truck’s exterior mirrors is 1.936 m (phantom vertical line). Figure B.2 shows the results for the bulldozer. The threshold value of the

bulldozer is approximately 2.5 m, resulting in 86.958% 3D blind spots volume. The necessary cab sphere radius is 1.479 m.

Table B.1: Sphere Radius vs. # Cubes for Equal Cube Size

$R_{\text{sphere}}$ (m)	# Cubes	Dump Truck Blinds Spots (%)	Bulldozer Blind Spots (%)
10	300	75.133	79.243
9	270	76.885	81.758
8	240	77.368	81.967
7	210	78.626	83.435
6	180	78.315	83.693
5	150	79.781	84.603
4	120	80.177	84.816
3.5	105	81.278	85.217
3.26666487	98	80.866	N/A
3	90	81.439	86.455
2.766665145	83	80.816	86.353
2.5	75	81.111	86.958
2.26666542	68	N/A	86.940
2	60	79.927	86.322
1.5	45	77.405	85.029
1	30	68.582	76.405
0.5	15	41.887	39.511

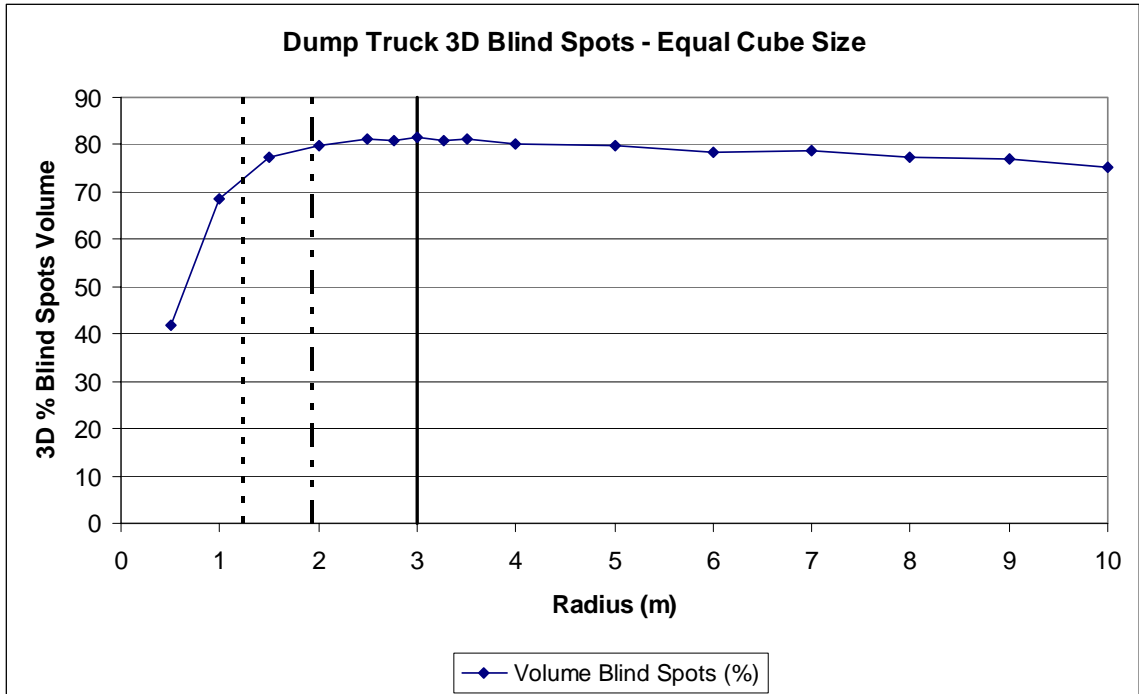


Figure B.1: Dump Truck 3D Blind Spots – Equal Cube Size

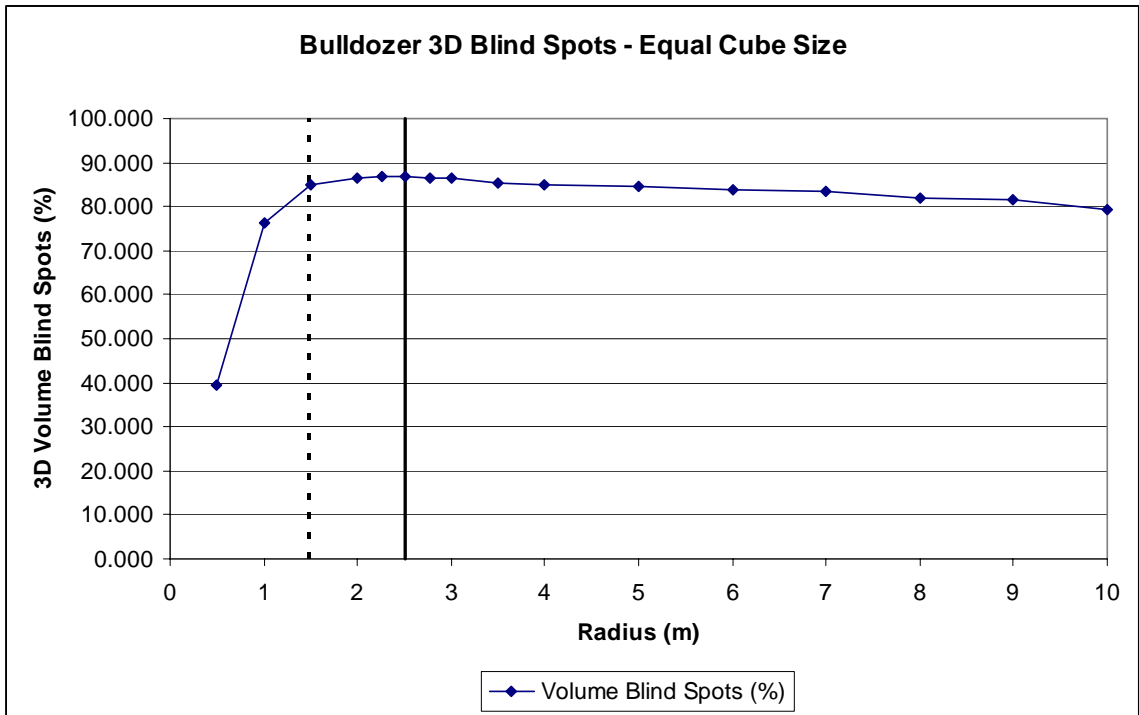


Figure B.2: Bulldozer 3D Blind Spots – Equal Cube Size